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16. ABSTRACT

The proceedings document a two-day radon diagnostics workshop at Princeton University, April 13-14, 1987. The proceedings comprise a consensus of current knowledge on important radon diagnostic techniques and how they may best be applied. That knowledge is summarized, placing the various radon diagnostic techniques in perspective. Diagnostic approaches offer improved evaluations of radon-related indoor air quality problems. An informed solution involves knowledge of the building, the building site, and the interaction of radon sources with the living space. The diagnostics are applicable in four phases of the mitigation process: (1) diagnostics that assess the radon problem; (2) premitigation diagnostics, from which a suitable mitigation approach must be selected; (3) diagnostics that check the performance of the radon mitigation solution; and (4) diagnostics that determine if the radon problem has been solved and that guideline radon concentrations have not been exceeded over the different seasonal conditions experienced.

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Abstract

Diagnostic approaches offer improved evaluations of radon-related indoor air quality problems. An informed solution involves knowledge of the building, the building site and the interaction of radon sources with the living space. The diagnostics are applicable in four phases of the mitigation process. The first phase consists of diagnostics which assess the radon problem. The second phase involves the pre-mitigation diagnostics. From this phase of the diagnostics a suitable mitigation approach must be chosen. Third are the important diagnostics that check the performance of the radon mitigation solution. Finally, the fourth phase of radon diagnostics determines if the radon problem has been solved and that guideline radon concentrations have not been exceeded over the different seasonal conditions experienced.

A consensus of current knowledge on important radon diagnostic techniques and how they may be best applied are the result of a two-day Radon Diagnostics Workshop sponsored by the U.S. EPA held at Princeton University, April 13-14, 1987. That knowledge is summarized, placing the various radon diagnostic techniques in perspective.

TABLE OF CONTENTS

Page

Abstract ii

Preface iv

A. WORKSHOP SUMMARIES 1

  I. RADON PROBLEM ASSESSMENT - M. Mardis, Chairman 1

  II. PRE-MITIGATION DIAGNOSTICS - L. M. Hubbard, Chairman 5

  III. MITIGATION INSTALLATION DIAGNOSTICS - M. Osborne, Chairman 10

  IV. POST MITIGATION DIAGNOSTICS - B. Henschel, Chairman 14

B. WORKSHOP PRESENTATIONS 18

  General Considerations Related to Radon Diagnostics 19
    J. Tell Tappan

  Use of Vehicle-Mounted Radiological Equipment in the Diagnosis of Houses with Elevated Levels of Radon and its Short-Lived Progeny 28
    C.S. Dudney, B.A. Berven, T.G. Matthews and A.R. Hawthorne

  Soil Characterization for Radon Availability and Transport 35
    C. Kuntz

  Overview of Selecting Radon Mitigation Methods 43
    T. Brennan

  Interim Report on Diagnostic Procedures for Radon Control 56
    B.H. Turk, J. Harrison, R.J. Prill and R.G. Sextro

  Guaranteed Radon Remediation Through Simplified Diagnostics 72
    D. Saum and M. Messing

  Follow-up Diagnostics - How Well Does the Mitigation Work and Does it Meet the Guidelines? 77
    K.J. Gadsby, D.T. Harrje, L.M. Hubbard and C.A. Decker

C. WORKSHOP DISCUSSIONS - Phase I - pg 81, Phase II-pg 101, Phase III-pg 109 & Phase IV-pg 118 80

D. ADDITIONAL MATERIAL - Supplemental Radon Diagnostics Information from the Piedmont Study plus diagnostic Master List 125

E. REFERENCES 151

F. ATTENDEES 161

PREFACE

The scope and objectives of the Radon Diagnostics Workshop were to gain an improved prospective, and to develop guidelines on the usefulness and range of applicability of different diagnostic techniques. To categorize state-of-the-art diagnostic methods, and to treat questions the diagnostic methods seek to answer regarding radon emination, transport, entry and indoor distribution, four phases of radon diagnostics were highlighted in the Workshop. These phases are:

I. Radon Problem Assessment Diagnostics: radon source strength and location, house characteristics, and house occupancy characteristics.

II. Pre-Mitigation Diagnostics: selecting the best mitigation system for the particular building taking into account radon "hotspots" and other special conditions particularly as related to the house substructure.

III. Mitigation Installation Diagnostics: used during installation of mitigation systems to assure proper operation.

IV. Post Mitigation Diagnostics: assurance that the radon guidelines have been met and that the mitigation system is adjusted properly.

The background of the attendees was varied, but much of their experiences with radon has been a direct result of the U.S. EPA, DOE and state programs attempting to understand and mitigate radon problems in primarily residential buildings. Examples of that experience come from states all over the U.S., as well as Canada.

A critical review of the effectiveness of current diagnostic procedures was part of the Workshop agenda. Panel discussions focused upon the various diagnostic methods with emphasis given to questions such as:

a) How good is the rationale for the diagnostic measurement?
b) How easy is the diagnostic procedure?
c) What resources and expenses are required to implement the diagnostics?
d) What information can be obtained from using the diagnostics?

The format of the workshop proceedings begins with summaries of each of the four phases of radon diagnostics. The summaries provide a quick overview of the topics discussed and conclusions reached in the discussions, and refer the reader to more detailed treatment of the various topics in the text that follows. The Workshop Presentations are a part of that text together with the Workshop Discussions.

The emphasis on diagnostics in radon troubled homes is a quest for additional knowledge as to the severity of the problem, the approach that may be used for solution of the problem and to evaluate the way the solution is working out. It was clear in the Workshop discussions that such diagnostics are absolutely necessary in some homes but many of the procedures are not cost effective in the homes that are simpler to mitigate. Anticipating possible radon problems at the house design phase is likely to prove more cost effective than extensive soil probing to quantify the radon problem potential for the individual building lot. Measurements to determine radon levels for the majority of our homes are generally recommended. In those areas of high incidence of homes with radon levels greater than the EPA guidelines and/or regions where very high house radon levels have been observed, every homeowner should check their house for radon concentration levels.

Where radon problems exist it is important to evaluate exactly what should be done. In homes with concrete basement floor slabs the diagnostic approach receiving wide acceptance is to check for communication under the slab. Subslab suction is commonly used to remove the radon gas via a fan and piping that exhaust to the outside, but diagnostics are necessary to make certain that suction extends over the entire slab. That openings through slab or basement walls need only be a few square centimeters, points out that just sealing the basement/crawlspace may not be enough, and that active or passive radon venting may be needed. A knowledge of how the house and its equipment function with respect to providing the pressure differences that drive the radon flow is necessary if the correct measures are to be taken.

Diagnostics after mitigation devices are in place are necessary to insure that the job has been done correctly. An informed homeowner or private testing agency is recommended for these checks so as to avoid the conflict of interest of a mitigator justifying his solution has been effective.

The Workshop treats these radon diagnostic subjects in depth, looking at the pros and cons of diagnosing the radon troubled house before, during and after mitigation. The techniques described are evolving rapidly in a field where discoveries are being made daily. However, many of the diagnostic approaches may already be viewed as "standard", while many others are in the process of being finalized.

The principal conclusions of the discussions of each phase of the diagnostics are given in the following summaries.

Radon Diagnostics Workshop, 1987. Phase I Summary

PART A WORKSHOP SUMMARIES

Phase I. - SUMMARY

RADON PROBLEM ASSESSMENT DIAGNOSTICS - M. Mardis, Chairman

1. Gamma Scans

- The National Uranium Resource Evaluation (NURE overflight data) would most likely be useful in identifying large land areas which would exhibit a higher probability of indoor radon problems. However, because of geological differences, and local hotspots, low readings should not be interpreted as an absence of a radon problem.
- Local gamma surveys such as "scan vans" or "on foot" methods may prove less useful than NURE global surveys because of the limited coverage. The van is limited by road access, while on foot surveys may be limited by time constraints.
- Isolated hotspots and depth of the radon sources place limitations on the information available from the various gamma surveys.

2. Soil Gas Measurements

- Soil Gas Measurements are another approach to accessing the probability of local indoor radon problems. High radon levels in the soil gas (thousands of pCi/L), combined with soil information (permeability in particular), can indicate the potential for elevated indoor levels. However, the number of measurements necessary to identify the radon problem potential for a particular construction lot could cost more than building radon prevention into a house. Hotspots may be missed in the survey, even with a large number of samples.
- The variability of soil gas measurements (i.e., a 10 to 100 fold

difference in levels within tens of feet) is a function of location (e.g., if the measurement is taken directly over a rock fracture or a few feet away with impermeable soil), and may be a function of soil parameters including moisture and type of clay or sand.

- Soil gas measurements seem to correlate with indoor radon values in areas where there is very homogeneous soil (Florida) but soil gas and indoor data do not seem to correlate well in areas with highly non-homogeneous soils.

- Soil gas measurements could be of use in identifying areas of concern on a regional, or "housing development" scale but not on a single lot basis. This could be confounded in an area of variable soil types.

- In the comparison of soil gas measuring methods, grab samples are preferred to alpha track and charcoal canister. Further protocol development is needed for soil gas measurements (i.e., where, when, how deep, and what type of measurement to make). Direct measurements of soil gas and soil permeability are preferred. Samples from at least one meter depth to avoid atmospheric dilution were recommended. Quality assurance and quality control procedures need to be developed.

- A cost benefit analysis needs to be performed to access the value/risk of using soil gas measurements versus building radon resistant houses on a regional and single lot basis. General feeling was that there would be a negative cost benefit when used on a single lot basis.

- Delineation of Terms for discussion of this topic area include:

Radon production = radium decay rate
Radon entry efficiency = indoor radon/soil gas contribution to

indoor radon level x 100.
Radon availability = Rn conc. in pores x mean migration distance.
Mean migration distance = f (soil characteristics and radon decay rate)

3. Problem House Identification

- The geological and the NURE data may be useful to focus indoor screening/measurement surveys. The only way to be sure about a house is to make a "closed house" measurement.

- Useful surveys could be based on prediction models and/or the "Fan Out" approach around discovery houses (where "fan out" means the use of high level houses as the centers for studing nearby homes).

All screening surveys should base design considerations on:

- sampling during winter "closed house" seasons
- areas with known elevated indoor levels
- sampling more frequently in areas with more elevated levels, i.e., sample every house in areas where a large percentage of the houses sampled resulted in levels 4 pCi/L.

4. Questionnaires

- Preliminary screening questionnaires are useful for research house selection and as an opportunity for mitigators to address whether confirmation measurements have been performed to substantiate the indoor levels. They may also ask questions which would provide basic information on major entry routes, basic construction type, etc.

- The preliminary questionnaire could identify activities which the homeowner could carry out to address the need for professional mitigation assistance.

- Pre-mitigation questionnaires and visual inspections are perhaps the diagnostician's primary and most useful tools. Homeowners should be consulted, but information could be suspect unless the homeowner can produce blueprints or pictures.

- The length of questionnaires and the questions asked tend to be a function of the experience of the diagnostician/mitigator and the construction type. Typical entry routes, if identified with early questions, might preempt other unnecessary questions or diagnostics.

5. Research Needs

- We seem to have a sufficient understanding of the major factors influencing radon entry and typical entry routes in some construction types to be effective mitigators in those types. (For example, basements and perhaps slab-on-grades where subslab ventilation systems have proven highly effective when reasonable communication is present under the slab.)
- There is a need for research in other construction types and combinations of building types. Basic research concerning radon production, transport and entry into buildings; so that we may better understand phenomenon we are dealing with and perhaps develop even better mitigation and prevention techniques.
- More research is needed in modeling and prediction/correlations between geological factors and indoor levels.

Phase II. - SUMMARY

PRE-MITIGATION DIAGNOSTICS - L. M. Hubbard, Chairman

1. Diagnostic goals of researchers and mitigators.

- During discussions of diagnostics techniques in general it is important to be aware that diagnostic measurements appropriate for research needs are in many instances different than those appropriate for use by mitigators. Researchers use pre-mitigation diagnostics to further their understanding of the basic mechanisms for radon transport into building structures. Some of the research has been directed towards developing specific diagnostic techniques that are most useful for mitigators to use. The mitigator on the other hand is interested in being able to mitigate a house successfully with a minimum of time invested in diagnostic measurements. The Phase II discussions attempted to separate these two approaches to diagnostics.

2. Mitigator current diagnostics

- The mitigators present at the workshop explained the diagnostic techniques they are currently using. They ranged from a visual inspection of the house to a walk through accompanied by some grab samples and differential pressure measurements and/or subslab and wall communications testing. Also discussed, but elaborated on in more detail in the formal presentations, was Saum's diagnostic technique. His "blower floor" procedure is tailored to a substructure with sufficient aggregate under the slab that near ideal conditions for subslab ventilation exist. The diagnostics are designed to assess the size and location of the system which should be installed, and have proved very useful under these conditions.

- There was generally agreement by the mitigators that with experience one can often successfully mitigate a building after only a visual inspection. This is perhaps true if subslab ventilation is the mitigation installed, partially because the success of subslab ventilation is dependent on at least some communication existing under the slab (which does occur in many homes). A visual inspection by an experienced person is often enough to decide upon the most expedient location for the subslab penetrations and the exhaust pipe and fan for the system.

- An installation with no diagnostic measurements, however, cannot assure that either too little or too much air (with an accompanying excess of basement air) is being drawn into the subslab ventilation system. Currently, however, many mitigators are using no pre-mitigation diagnostics. They are installing subslab ventilation systems and using post mitigation radon concentrations to motivate any necessary system alteration.

- Subslab ventilation is the mitigation system for which the most diagnostic measurements have been developed and performed, to date.

- The most important and useful test in this category is communications testing. A vacuum cleaner is commonly used to pump on a given hole through the slab and the induced change in air flow (speed but most importantly direction) is monitored through other holes which have been drilled through the slab and temporarily sealed. In some cases a variable speed pump is used. Good communication means that sucking on one hole with a vacuum cleaner will cause air to flow through each of the other test holes into the subslab space. The same test can be done for within wall and subslab to wall communications.

3. Researcher current diagnostics

- The research community is currently working on quantifying the degree of communication obtained by a known pumping source (and how much is necessary to maintain subslab depressurization under a variety of conditions) by measuring the air speed and direction and pressure differential through each test hole under a variety of conditions.
- Grab samples are used in pre-mitigation diagnostics to determine the location of radon hotspots. This can be attempted by collecting grab samples from various test holes through the slab, in the hollow block walls (if they exist), and in any cracks or holes or sumps that exist. The radon concentrations in these various spots, along with the air velocity and the cross sectional area through which the air is moving, will give an estimation of the radon source strength at each test location.
- Grab samples of soil gas collected outside the perimeter of the house (generally from metal pipes which extend one meter below the soil surface) along with a soil permeability measurement at the same location have been used (mostly by researchers searching for some association between soil gas radon concentration and soil permeability) to determine which sides of the house may need more attention in the design of the

subslab ventilation system, i.e. where the radon entry points may be the most significant. Unfortunately this diagnostic procedure has not proven to be very useful.

4. Blower door testing

- Blower door tests are used for a variety of purposes in pre-mitigation diagnostics. Regular blower door tests, which relate the amount of air flow into (or out of) a house which maintains a specific amount of pressurization (or depressurization), are used to estimate the effective leakage area, i.e., the "leakiness" associated with a particular house. If the test is applied to the basement area alone it is possible to determine the amount of air flow necessary to maintain a basement pressurization of between 5 and 10 Pascals. This is the amount of counter-pressure which should be sufficient to prevent convective entry of radon gas. If the air flow determined from the blower door test is less that about 350 cfm, (ideally below 200 cfm), basement pressurization may be a viable mitigation strategy if subslab ventilation is not suitable.
- Another use of a blower door test is to determine what amount of air exchange is needed in the basement or crawlspace for a Heat Recovery Ventilator to effectively remediate a radon problem.
- A depressurization of the substructure to -10 Pascals can be used in the summer to simulate winter conditions, although there is some question as to the reality of this simulation. In this -10 Pascal depressurized mode, grab samples, pressure differentials, and air velocities through the test holes can be recorded (as described above) and used to determine

radon source strengths at specific points in the depressurized mode.

5. Tracer gas measurements

- Tracer gas measurements can be used in pre-mitigation diagnostics to augment communications testing. Also, leaks through the exterior of the substructure can be located using tracer gas techniques (and sealed if a tighter basement is necessary for success of a basement pressurization system). Tracer gases can be used for finding a footer drain.

6. Grab sample questions

- Questions still remain regarding the extent to which grab samples should be used. Questions arise because of the diurnal and seasonal variability in the radon content of the soil and subslab gas and the dependence of this variability on both environmental and house specific parameters. These variations need to be better characterized.

Phase III - SUMMARY

MITIGATION INSTALLATION DIAGNOSTICS - M. Osborne, Chairman

Four distinct radon mitigation approaches were discussed along with their related diagnostic procedures.

1. Sealing

- Sealing was the first mitigation method mentioned, where Canadian studies indicate that a total area equal to one square centimeter opening in the basement slab or walls is all that can be allowed if the sealing approach is to be successful. Quality control is extremely important, as well as the choice of materials. Epoxies often don't bond well with themselves; they require special surface preparation, and bonding to the surroundings is vital.

- Sealing is viewed as expensive and difficult but not an impossible task. The best success would be anticipated in new construction where one needs an experienced team using common sense in the choice of sealing methods. A specific recommendation was the use of a sealant such as a solvent-hardening, rubberized asphalt.

- Radon flux measurements, as a diagnostics tool, point out the effects of even pinhole leaks. Tracer gas methods are also recommended as a method of assessing radon leakage paths and whether or not sealing is successful.

2. Dilution

- Dilution was the second general method discussed for radon mitigation. Cautions with this approach include making certain the airintake isn't near radon sources or located close to the ground, and avoiding short circuiting (air exiting prior to complete mixing).

- The ultimate desire is to set up a plug flow situation, i.e., where an air flow sweeps away pollutants rather than mixing them with interior air.

- Diagnostics for dilution methods include the use of the blower door to evaluate the envelope leakage rate of the house as well as to catalog bypass leakage areas which allow radon to move within the building. For example, unless appropriate tightness levels are present it may make no sense to use heat recovery ventilation. The blower door tests can also be used to evaluate communication between zones. Pressure measurements can be used to make sure that pressures indoors are slightly positive rather than negative to avoid drawing radon into a living area.

- Air flow measurements may make use of pitot tubes, heated-wire anemometers, vane-type anemometers, etc., in ducts or pipes. A grid-type measurement, such as a pitot tube grid, is a superior approach to averaging flow profiles.

- Tracer gas measurements are also very useful in flow measurement and air movements, as well as detecting leaks in the system.

- Use of a continuous radon monitor as a diagnostic tool allows exhaust air radon concentrations to be evaluated, and to make certain exhaust flow isn't being reintroduced to the house by the supply air.

- Because of shorter air residence times, dilution may result in reduction of working levels greater than the radon levels themselves.

Radon profiles (multi-location testing) may be used to check for hotspots. One approach is to flush out the radon with high initial ventilation and then observe the ingrowth of radon. This diagnostic method may be used to evaluate the amount of ventilation required to meet EPA guidelines.

3. Pressurization

- Pressurization of the basement was the third category discussed. Separation of the basement/crawlspace from the upstairs is an initial requirement. If upstairs air is used to pressurize the basement, care must be taken with the venting of upstairs combustion devices.
- Use of the blower door is recommended to check for air leaks between zones, crack leakage to the outside, and back drafting of appliances. Flows of approximately 500 cfm, and pressure differences of at least three pascals are provided as representative numbers for judging airflow requirements for pressurization.
- Turning on all venting appliances and checking whether the system maintains proper pressurization is one way to check performance adequacy of the ventilation system.

4. Subslab depressurization

- Subslab depressurization was the fourth approach discussed. Using the slab as the separation between house space and soil gas, depressurization of the subslab must be sufficient to overcome stack effects (buoyant airflow in the house that depressurizes the basement) and venting appliance operation since the resulting basement depressurization can cause soil gas to move through the slab and walls to the living space.

- Sensitive pressure measurement techniques (such as electronic digital manometers) may be used for evaluating the pressure differences and smoke tracers can determine the direction of air movement. The lowest pressure drop locations across the slab are the critical zones and should not be located near any radon hotspots.
- Since the exhaust from subslab depressurization tends to contain high radon concentrations, avoiding re-entrainment is essential; tracer gas techniques work well in this check.
- The exhaust also often contains high levels of moisture, making it essential to design piping to avoid water accumulation and eliminate possible pipe blockage.
- Again back drafting of the combustion appliance can be influenced by the operation of the radon mitigation system since air is being removed from the house substructure. Indication of spilling of exhaust products into the space may be documented by a small temperature-sensitive "tab" at the flue entry. Spillage tends to be worst at start of combustion appliance operation. Use of blower door techniques can also supply information on the required air leakage necessary to supply combustion devices. Dedicated make up air to the appliance is highly desirable.

Radon Diagnostics Workshop, 1987. Phase IV Summary

Phase IV. - SUMMARY

POST MITIGATION DIAGNOSTICS - B. Henschel, Chairman

Radon monitoring

o Radon monitoring is the principal post mitigation diagnostic test commonly utilized by commercial mitigators. The first question is -- should the emphasis be on measurement of radon or radon progeny? Currently most people measure radon gas. One reason is that it is simpler to measure radon gas -- i.e., charcoal canisters, and alpha track detectors. Radon measurements might provide a less ambiguous indication of mitigation performance. Radon might even provide a better indication of health risk (given that only a relatively inexpensive measurement can be made, and that the WL - versus - particle size measurements needed for dosage/risk models are thus impractical for routine use); the radon is tracked by reading the value for Polonium-218, which -- as the daughter with the greatest fraction unattached -- probably represents the largest contribution to the health risk. There is a need for technical clarification of the EPA guideline of 4 pCi/L or 0.02WL because it is known that the equilibrium value relating radon and radon progeny varies by up to fifty percent. From a policy perspective, however, the guideline is sufficient as it is expressed (4 pCi/L or 0.02WL) because no specific equilibrium condition is specified or implied. In other words, the EPA action level is reached when concentrations of radon exceed 4 pCi/L or radon progeny exceed 0.02WL.

2. Who makes the measurements?

o Post mitigation radon monitoring also involves the question of who makes the measurement? A mitigator faced with the question of liability needs a direct knowledge of how the mitigation system is functioning. Also, information on the success of the mitigation method aids the mitigator in selecting mitigation approaches for other homes. The homeowner is concerned that the problem has really been solved and might want an independent measurement, made by someone other than the mitigator. Federal or state government representatives may be most interested in how well the mitigators are performing from a public health standpoint, and therefore may desire an independent evaluation of radon levels. These results may dictate which mitigators are placed on a "recommended list", where states maintain such a list.

3. Length of testing

- The next question involves the length of testing. Short-term monitoring is essential, immediately after radon mitigation system installation, to confirm that the system is functioning properly. In addition to this immediate measurement, an integrated measurement over two to three months (alpha track) in the winter (to provide a worst case test of the system over a reasonable time period) is a recommended minimum evaluation.

- The need to develop two-week monitors as an intermediate measure was also discussed.

- Arriving at an annual average radon exposure is a point that needs further clarification; if the 4 pCi/L guideline is interpreted as the annual average that a homeowner should try to achieve, then measurements might cover a full year.

- Multi-year monitoring could be valuable in evaluating changes in mitigation system efficiency and/or variations in the radon source strength over time. Annual and multiyear measurements would probably not be conducted by the mitigator, but would be the responsibility of the homeowner, or might be carried out by researchers or state agencies.
- Inexpensive monitoring devices may be heading to the market place to help solve some of these radon monitoring problems.

4. Where do you monitor?

- Measurements are normally done in more than one location: in the living area, both upstairs and downstairs, in the basement/crawlspace, and in those locations cited by the homeowner as important. Protocols must specify monitoring location.
- By surveying the radon levels throughout the house (radon profile), one is less likely to miss a high radon area, and also these data can be the basis for estimating total occupant radon exposure. The basement (or perhaps crawlspace) area normally registers the highest radon levels and thus is most sensitive in revealing if any radon problem still exists after mitigation.

5. What monitoring techniques are being used?

- Charcoal canisters and alpha track detectors are popular because of ease of use and relatively low cost. For immediate radon level information, grab and continuous radon sampling are popular. There remain several uncertainties associated with the interpretation of grab sample data because of the large variation in indoor radon levels (which is evident from continuous radon data).

- In view of all the uncertainties, there would appear to be a need for a standardized procedure that could be routinely applied in the post mitigation period.

6. Other diagnostics

- Diagnostics other than checking radon concentrations are usually not done routinely by commercial mitigators.
- Testing of the final pressure field under the slab after installation of a subslab ventilation system was emphasized by several of the workshop participants as an important item to consider as a post mitigation diagnostic measurement.
- Assurance that combustion devices are not back drafting is also an important post mitigation measurement to make.
- Measurement of flows and pressures in the piping associated with the mitigation system can be important in the post mitigation diagnostics as well as during system installation.
- Mounting a gauge on the piping to indicate proper system function is being used and is a form of post mitigation diagnostics that provide assurance to the homeowner that the system is functioning satisfactorily.

B. WORKSHOP PRESENTATIONS

The following presentations preceded the actual workshop discussions. The purpose was to introduce the workshop attendees to the spectrum of radon diagnostic subject matter presented by researchers and practitioners who represented the cutting edge of radon diagnostics and mitigation technology. These presentations, of necessity, were concise, but the workshop participants were given adequate time to pose questions to gain more detailed information on those areas of particular interest. Further references were provided in many instances, and a reference section has also been included in this workshop summary.

The work described in this paper was not funded by the U.S. Environmental Protection Agency. The contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

GENERAL CONSIDERATIONS RELATED TO RADON DIAGNOSTICS

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1.0 INTRODUCTION

Numerous diagnostic techniques have been used for determining the existence and extent of a radon problem. These techniques are generally categorized in four sequential phases; initial problem assessment, pre-mitigation, mitigation installation, and post-mitigation. This paper presents a general overview of the various techniques used during these four basic phases of diagnostics.

2.0 INITIAL PROBLEM ASSESSMENT

Diagnostic techniques used for this phase can be applied to open land areas, as well as existing structures and their sites. The normal approach includes identifying areas that are geologically prone to radon, and then surveying specific sites within the radon-prone area to confirm the presence of a radon problem. The sequence of diagnostics related to this initial assessment is discussed below.

2.1 Geologic Characterization

A review of individual state geologic maps serves as the basis for identifying potentially elevated radon areas. The primary geologic formations that accommodate elevated radon are as follows:

- Granitic Rocks

  Granitic formations are generally associated with higher concentrations of uranium than other formations. The uranium enrichment occurs naturally due to the geochemical composition. Additionally, fractures are routinely associated with granites, and the fractures accommodate remobilization and concentration of uranium within the fractured areas.

- Marine Black Shales

  These formations are primarily carbonaceous (plant derived material) shales, and in many cases low concentrations or seams of coal are related to the shales. The carbonaceous materials tend to absorb uranium during initial deposition. Additionally, uranium migration associated with ground water results in enriching the carbonaceous materials, since these materials essentially act like a sponge relative to the radioactive materials.

- Silty Shale Containing Phosphate

  These formations are always naturally enriched with uranium. Many phosphate milling operations actually reclaim the uranium (yellow cake) from the phosphate tailings on a profitable basis. It is not uncommon to find uranium concentrations ranging from 50 to 100 ppm in these formations.

- Thorium and Rare-Earth Occurrence

  These occurrences are generally related to several geologic characteristics; alkalic rocks, carbonatites, senites, granites, and in veins. The U.S. Geological Survey has two open-file reports, 79-576T and 79-576U, that have mapped these occurrences within the conterminous United States.

- Soil Permeability

  Review of state geologic maps can assist in characterizing permeability of soils that overlay geologic formations of concern. These data are useful in estimating radon emanation to the soil surface.

2.2 Gamma-Ray Anomalies

Gamma-ray anomalies can be related to daughter products of uranium, thorium, and potassium. In the case of uranium, the daughter product bismuth-214 (which is also a radon daughter) can contribute to the gamma-ray anomaly. Identification of these anomalies is generally based on a historical data review and field surveys as follows:

- Historical Data

  In 1974, the U.S. Department of Energy (DOE) initiated the National Uranium Resource Evaluation (NURE) program. This was prompted by the need to address concerns over the available uranium supply for nuclear reactors. Aerial radiometric surveys were flown, using sensitive gamma-ray spectrometers that measured uranium, thorium, potassium, and bismuth. All but four of the quadrangles in the conterminous 48 states were surveyed; 99 of 154 quadrangles in Alaska were also flown. The flight line spacing varied from a quarter mile in detailed surveys to six miles in areas not expected to contain significant uranium concentrations. Maps produced by the DOE depicting the uranium occurrences identified by this survey are useful in defining the naturally-occurring concentrations of radon on a regional basis.

Many states have completed gamma-ray surveys using mobile gamma scanning vans or hand-held portable gamma scintillometers. These survey results have been mapped by the appropriate states and they are useful in defining near-surface anomalies that will produce radon problems.

- Field Surveys

  A gamma-ray scintillation detector incorporating a multi-channel analyzer has been mounted on a van-type vehicle to accommodate a mobile survey within areas of concern. The detector is normally shielded to direct sensitivity to a single side of the mobile unit. A recorder is incorporated with the system, and recorded gamma anomalies are related to physical location by hand. Accumulated data are useful in identifying specific structures or building sites where there is a high probability of elevated radon.

  Gamma-ray surveys are also performed on foot using hand-held scintillometers. For individual building sites a scanning technique, with the detector about two inches above the surface, is used and data are recorded on a 10-foot grid basis. Existing structures are also thoroughly scanned and data are recorded on an appropriate floor/plot plan sketch. Anomalies identified are useful in identifying specific "hot" spots where elevated radon is likely.

2.3 Soil Radon Gas and Flux Rate Measurements

Soil radon characterizations are particularly useful in diagnosing open ground areas planned as building sites. Two techniques are normally used; one that measures the radon concentration contained in the near surface soils, and one that measures the radon flux rate on the surface area. These techniques are discussed below.

- Soil Gas Radon Concentrations

  Alpha track film detectors are normally used to make these measurements. The detectors are normally placed on the surface soil in a grid pattern over the area of interest; areas where gamma-ray anomalies have been identified are always included in the sampling. Detectors are also placed over or within soil boreholes of varying depths to accommodate soil gas measurements from subsurface soil layers. Data from the alpha track film are plotted on an appropriate plot plan map; this mapping shows a soil gas profile over the area of interest. These data are useful in determining the soil radon concentration related to a specific location planned for building. To date, a precise method for relating these measurements to an indoor radon concentration has not be determined.

- Radon Flux Measurements

  Two radon flux measurement techniques are commonly used; charcoal absorption and accumulator. Since radon transport or migration through soil is highly dependent on soil permeability, moisture and several other parameters, flux measurements are normally made at the location of a hole (dug or bored) that represent the footing depth of the planned structure. Measurements are made in units of pico-Curies of radon per square meter (pCi/m^2). The resulting data is related to a flux rate of < 2 pCi/m^2 which is associated with soils where the habitable structures do not contain elevated radon concentrations. Areas measuring in excess of 2 pCi/m^2 can be expected to produce a radon problem in an enclosed structure.

2.4 Structural and Occupancy Characteristics

Visual inspection of the structure and general habits of the occupants are important factors related to indoor radon problems. The structure design and condition of structural components have a direct relationship to the problem since these parameters can either produce a radon barrier or an influx route. Additionally, occupancy characteristics have a significant relationship to the air exchange rate and indoor pressure differentials associated with the structure. Techniques normally used to diagnose these characteristics are discussed below.

- Visual Structure Inspection

  This technique includes identification of apparent major radon influx routes such as open soil areas, sumps, structural cracks, fence drains, porosity of structural components, and use of exhaust fans. These observations are normally recorded on a standardized form, and the data is useful for evaluating complexity relative to possible remediation.

- Occupancy Characteristics

  This technique includes having the occupants fill out a standardized form indicating the number and age of occupants, smoking habits, occupants that work outside the home, and other data that can be related to the occupant-induced ventilation of the structure. Additionally, other related data are normally obtained during structure inspections through conversation with the occupant.

2.5 Indoor Radon Profile

This diagnostic effort includes measurement of radon and radon decay-product concentration (RDC) in various zones or regions of a habitable structure. Several measurement techniques are routinely used that can generally be categorized in three groups; grab sampling, integrated monitoring, and continuous monitoring.

Resulting data are useful in identifying concentration gradients that indicate regions of significant radon influx or stagnant air. Additionally, simultaneous radon/RDC measurements will identify the equilibrium state of the decay product, and the age (equilibrium state) of the decay products can be related to the air exchange rate of the structure. The techniques used to obtain this profile data are discussed below.

- Grab Sampling

  This technique includes collecting simultaneous radon and RDC measurements from various locations representing all indoor areas of the home. Equipment includes radon scintillation cells, low volume air sample pumps incorporating a glass fiber filler, and appropriate photo-multiplier tube detectors with scalers.

  The number and location of samples required is site specific depending on the number of floor levels and configurations of room partitioning associated with the home. The following sample location selection criteria will generally apply:

  - Basement - Usually a minimum of two locations, one in either end; however, can require four locations in basic quadrants if partitioning indicates isolation of one area from another.

  - Crawl spaces - Usually one location near the center of the crawl space, followed by one location in the living space directly above the crawl space location.

  - Main floor above basement - Usually a minimum of two locations, one in the main living space and one in the opposite end of the house in a closed bedroom.

  - Third level of two story house - Usually one location from closed bedroom; an additional sample is required if open living area is present.

  In summary, radon profile sample locations required for each home will vary from a minimum of 4 to as many as 9.

  Accumulated data are normally summarized on an appropriate "standard" form. The radon and related RDC is recorded for each sample location, and the equilibrium state of the RDC is calculated for each location. These data are averaged to show the overall house radon and decay product concentrations as well as the average equilibrium state.

With respect to the measured equilibrium, 50-percent equilibrium is equivalent to 38 minute old radon decay products, which equates to approximately 1.6 air exchanges per hour. This information is a "rule of thumb", since decay product plate-out and other factors are ignored. However, the data is useful in determining structure ventilation prior to and during sampling, and it serves as a good indicator of the validity of the sampling effort.

- Integrated Monitoring

  Carbon canisters, alpha track film, and the Environmental Protection Agency (EPA) Radon Progeny Integrating Sampling Unit (RPISU) are commonly used to accommodate this radon profiling technique. The sampling device is placed in a single area of interest, or in various regions of the house as discussed in relation to grab sampling.

  Normally measurements are made over a 2 to 5 day period, and results are interpreted over this sampling period. These data are useful in identifying areas of primary radon influx, as well as for confirming the presence of an indoor radon problem.

- Continuous Monitoring

  Several manufactures produce continuous monitors for measuring radon or radon decay-product concentrations. These monitors are deployed in a specific area of concern or various zones of the indoor area. Sampling periods should be a minimum of one hour, and sampling periods of up to several days can be accommodated. Resulting data are useful in providing relatively prompt information regarding concentration gradients, and confirmation of a radon problem is easily obtained.

3.0 PRE-MITIGATION

This phase of diagnostics accommodates collection of data from indoor areas, and these data are the basis for identifying appropriate site specific radon mitigation techniques that can be applied to the structure. The basic techniques used can be generalized in three categories; radon grab sampling of structural components or zones, radon flux rate measurements from structural components or features, and pressure measurements and alterations. These techniques are briefly discussed below.

3.1 Radon Grab Sampling

Flow-through type radon scintillation cells are normally used to accommodate this diagnostic effort. Samples are collected from inside hollow walls (through a drill hole or from behind an electrical switch plate), from water drain sumps, from beneath concrete floor slabs (through drilled holes), or any other structural component or area of interest. Resulting data identifies areas or components with significant radon concentrations that may be suspected as major contributors to the indoor radon problem.

3.2 Radon Flux Measurements

The charcoal absorption or accumulator methods are normally used to accommodate these measurements. The sampling device is sealed over the surface area of interest for a timed interval, and resulting data is calculated in pCi/m^2. Sample collection locations normally include each basement foundation wall, the floor/wall joint, the solid floor, and any structural cracks that could accommodate significant radon entry. The accumulated data provides a comparison of the radon source significance related to structural components or features sampled. This information aids in determining which structural feature should be mitigated to obtain the most significant radon reduction.

3.3 Pressure Measurements and Alterations

These diagnostics normally incorporate use of fans, blower doors, pressure and air flow rate measurement devices, and tracer in gases. Pressure differentials are measured in areas of interest and indoor zones. Specific areas or zones in the house are pressurized or depressurized through use of fans, connections through floor slabs or into walls, and blower doors as appropriate. Radon sampling is normally performed between each induced pressure change to determine the effect on radon concentrations.

Air movement and velocities are measured through structural test holes to identify communication from one point to another. Inert tracer gases are often injected in areas of interest and resulting measurements are also used to determine communication between specific points.

Blower door tests or inert tracer gas injections are normally used to evaluate the building envelop tightness. These techniques will be discussed in detail by other workshop participants.

In summary, pressures are recognized as a dominating factor relative to radon influx rates. Diagnostic techniques used are highly variable as is the equipment incorporated with the techniques. Information gathered is useful for determining the effect of occupant or meteriologically induced pressure charges.

4.0 MITIGATION INSTALLATION

Diagnostics used for this phase include measurements and observations to assure the quality and integrity of the installed mitigation system. These parameters are discussed below:

4.1 System Quality

The primary quality factors are materials used, craftsmanship applied, and the cosmetic effect the system has on the interior area. Quality products must be used, and installation must be accomplished using industry craftsmanship standards. In all cases, system installation should be accomplished in a cosmetically acceptable and pleasing manner to the extent that is practical.

4.2 System Integrity

Diagnostics to assure system integrity includes balancing air flow within the system, tracer gas injections to identify leakage or determine exhaust backdraft, and pressure differential measurements in specific areas or zones.

Simple smoke tube techniques can usually identify significant single point system leakage or backdrafts, however, other tracer gases injected into the system will provide better identification of leakage related to several small points that are significant when combined.

Pressure differential measurements from specific areas and zones will identify system induced changes that may affect the radon influx. It is possible to create a negative pressure with an active mitigation system, and this will normally result in increased radon influx. Conversely, over pressurization of a radon influx zone will either reduce the influx rate or force increased radon concentrations into other areas of the structure.

5.0 POST-MITIGATION

Diagnostics related to this phase will identify the most efficient operational mode of the mitigation system, and evaluate the systems overall performance relative to desired indoor radon reduction. After the operational efficiency and overall effectiveness of the system has been determined, various appropriate diagnostic measurements discussed previously may be required in the event indoor radon concentrations remain above the desired level. These aspects of diagnostics are discussed below.

5.1 Effectiveness Evaluation

The indoor radon profiling techniques, previously discussed in Section 2.5, are normally used to determine radon/radon decay-product concentrations in various areas or zones throughout the structure after the mitigation system is activated. These data provide relatively prompt information regarding radon reduction achieved. If the mitigation system incorporates blowers or fans, speeds of these units are increased or decreased to obtain maximum radon removal and energy efficiency; re-sampling radon profile locations is accomplished after each adjustment to accommodate this evaluation.

5.2 Additional Remediation Considerations

If the post-mitigation effectiveness diagnostics indicate need for additional remediation, various techniques (discussed previously) are used to determine appropriate options. Since these techniques have been discussed previously, the following simply lists techniques commonly used in the order of personal preferences:

- Radon flux rate measurements to determine primary structural contributors remaining.

- Radon grab sampling from structural areas sampled during pre-mitigation diagnostics and other suspect areas to determine elevated sources remaining.

- Re-measurement of delta pressures, air flow rates, and air movement directions to determine need for further system balancing.

- Additional visual examination of structure characteristics to identify any possible oversights.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

Use of Vehicle-Mounted Radiological Equipment in the Diagnosis of Houses with Elevated Levels of Radon and Its Short-Lived Progeny*

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I. Introduction

Since the discovery of American homes with levels of indoor radon** progeny far in excess of the levels allowed in underground mines by governmental regulations, there has been greatly increased awareness of radon in residential environments. Homes with high levels of indoor radon have also been identified in Scandinavia. Underground miners exposed to radon progeny have experienced elevated incidence of fatal lung cancers and it is suspected that residential exposure may also lead to cases of lung cancer. Nero et al. (1986) have estimated that 1 to 3% of American homes have annual average levels of radon in excess of 296 Bq/m^3. The federal government (U.S. EPA and CDC, 1986) has estimated that lifetime exposure to levels of radon above 296 Bq/m^3 will increase lifetime absolute risk of fatal lung cancer by at least 26 chances in 1000.

Many factors are important in the identification of houses with elevated levels of radon. Since indoor radon comes predominantly from the rock and soil near a house, geological factors are important. Occupant behavior, building structure and weather are important factors because exchange of indoor and outdoor air is a principal means of dilution of indoor radon. This paper will briefly discuss the use of vehicle-mounted equipment in the assessment of some of these factors, principally building and geological ones, in studies that either seek to identify houses of concern or to identify radon entry points and sources in selected houses. Emphasis will be given to work that has been performed by Oak Ridge National Laboratory (ORNL) staff during the last ten years.

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**References to radon in this paper refer to ^{222}Rn unless otherwise noted.

II. Description of Vehicles

Two principal types of vehicles have been used by ORNL staff in their radiological surveys. The radiological scanning vehicles have been used to investigate spatially dependent anomalies in the gamma radiation field at selected locations. The mobile radiological laboratory has been used to provide logistical support to surveys requiring radiological measurements at sites that may lack electrical power or other requirements.

A. Scanning Van

A mobile gamma scanning system has been developed for the U.S. Department of Energy (DOE) by ORNL staff. The unit was originally developed in 1979 and its performance was enhanced following a research and development project in 1981. The vehicle provides continuous nuclide-specific analyses while in motion.

The detection system consists of a NaI(Tl) crystal, shielded so that photons principally originating from the passenger side of the vehicle are detected. The system is controlled by the operator through an on-board computer, with data output provided to the computer monitor, strip chart recorders, and a printer. Data are also stored onto floppy disks. Multichannel analysis capabilities are provided for qualitative radionuclide identifications. A ^{226}Ra-specific algorithm is currently employed to identify locations containing residual radium-bearing materials.

The primary mission of the mobile scanning van is to locate and identify those building lots on which there is evidence of residual radioactive material above local background levels. Typically, the scanning surveys are conducted as the final stage of the identification process and are used to (1) document locations that were identified from historical records, (2) provide ground-level surveying in support of aerial survey efforts, and (3) screen large areas of a residential neighborhood on a street-by-street basis. In identifying lots where contaminated materials exist, the scanning system is used to detect changes in the gamma radiation field associated with the site, as observed from accessible roadways or other public thoroughfares.

B. Mobile Radiological Laboratory

The staff at ORNL have also developed two mobile radiological laboratories. During surveys, a mobile laboratory can serve as a control center as well as housing instruments and other needed equipment. Each vehicle is a modified motor home equipped with its own electric generator, desktop computer, and radiological instruments. The radiological capabilities pertinent to radon diagnosis that can be performed on site include analysis of short-term samples for airborne radon and airborne progeny from ^{222}Rn, ^{220}Rn, and ^{219}Rn. A detailed description of these techniques is given below. In addition, crude radiological analyses of soil can be performed using NaI(Tl) well detectors.

III. Identification of Houses for Further Study

Because only a small fraction of U.S. houses are currently thought to require remediation for radon progeny exposures, it will be necessary to identify those residences needing further evaluation. In cases where the radon precursors are inhomogeneously distributed in the soil, it has been possible to investigate the gamma radiation field near houses while avoiding intrusions onto private property by using the mobile scanning van. These kinds of studies have allowed investigators to target residences for more detailed assessments. In cases where radon precursors are more homogeneously distributed, the only methods identified so far for identification of potential problem areas have involved geological assessment or untargeted measurements within houses and will not be discussed here.

A. Uranium Mill Tailings

Currently there is a large ORNL field office near Grand Junction, Colorado, out of which health physicists, geologists, and other ORNL staff are assisting in the identification of houses and building lots that are eligible for remediation under the Uranium Mill Tailings Remedial Action Project. Federal law, as implemented by 40CFR192, stipulates that DOE will offer to remediate buildings or homes at which there is evidence of mill tailings from the government's uranium mining programs in the 1940's and 1950's. Properties can qualify in various ways for this program, one of which is demonstrating both annual average radon progeny levels in excess of 0.02 WL* and the presence of uranium mill tailings. This program provides for the removal and replacement of soil around qualifying buildings and residences.

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*One working level (WL) means any combination of short-lived radon progeny in one liter of air that will result in the ultimate emission of 1.3×10^5 MeV of potential alpha energy.

To facilitate the completion of this program, radiological scanning vehicles have been used to identify potential candidate houses without intruding on building occupants. By slowly driving the scan van, described in Section II.A, down public roads it is possible to flag sites of radiological anomalies. In this case, the anomalies for which a search is made are those related to emissions from ^{226}Ra or ^{232}Th progeny.

B. Radioactive Waste from Dump Sites

There is a similar need for remediation in areas where soil from radiologically contaminated landfills has been used for backfill around homes. For example, in West Orange, New Jersey, waste from a radium dial painting facility was disposed of at several landfills in the 1930's and 1940's. Subsequently, houses were built above some of these landfills and there is now an effort to remove the radium-containing soil from near the adversely affected houses. When there is reason to suspect that some homes in a region may have a problem but it is not possible to identify them explicitly from historical records, then the use of a scan van or similar vehicle may be warranted.

IV. Identification of Sources Within the House

After a house has been identified as having a radon problem, there are potential uses for vehicle-mounted equipment in the identification of points of entry. The techniques historically used at ORNL will be discussed here. With the recent advent of more compact, light-weight electronic equipment, alternative methods are available to make some of these assessments.

A. Radon

Air samples collected near a single point in space and over a relatively short interval of time (i.e., less than 5 min), can be used to estimate the spatial distribution of radon levels within a residence. In this way, entry points with significant elevation of radon gas may be located.

A modified Lucas cell is used to measure radon (Volchok and dePlanque, 1985). The cell consists of a 500-mL plastic flask with interior surfaces coated with zinc sulfide. Room air is transferred into the flask and it is held for at least 4 h to let all preexisting radon progeny decay. The flask is then placed in a counting well on the vehicle and total alpha activity determined with a photomultiplier and a single channel analyzer. Currently, there are commercially available, battery-powered, portable systems that perform the same function.

B. Radon and Thoron Progeny

Another indicator of radon (or thoron, ^{220}Rn) entry points is measurement of progeny levels to estimate the spatial distribution. Due to the short half-lives of these species, more complex techniques are employed to measure levels of specific airborne progeny.

To collect a sample of airborne radon or thoron progeny, room air is pumped through a filter with pore size less than one micron. Most progeny, both attached and unattached to particulate matter, will be trapped on the filter and can be analyzed for alpha activity. The protocol used at ORNL has called for drawing 100-200 L through a 0.45 um filter in ten min. The filter is then taken to the mobile radiological laboratory and mounted below a surface barrier detector with helium gas flowing over the surface of the exposed filter. The helium serves to reduce the energy dispersion of observed disintegrations of any given alpha energy. Between 2 and 12 min and between 15 and 30 min after the cessation of pumping, energy-resolved data from the detector are acquired into a 512-channel analyzer. Using the algorithms of Perdue et al. (1980), concentrations of progeny from ^{222}Rn, ^{220}Rn, and ^{219}Rn can be estimated.

C. Working Level Ratio

Another indicator of radon entry points that may be used in the future is the ratio of progeny levels to radon levels. As radon-containing air ages, the progeny to radon ratio increases. Using the techniques described above or equivalent ones, it is possible to measure radon and its progeny at nearly simultaneous times at several locations. Figure 1 summarizes data from a survey of 70 houses in four states and shows that on average, air in basements has a 36% lower ratio of progeny to radon compared to air sampled on the floor above the basement.

V. Identification of Sources Away from the House

The scanning van has been used to investigate the relative abundance of ^{226}Ra in various geological strata near some houses with elevated radon levels. In Huntsville, Ala., four of eight houses studied had radon levels between 740 and 2220 Bq/m^3 (Dudney et al., 1987). A team of geologists investigated the geological strata in Madison County to determine which strata contained significant levels of ^{226}Ra. Of eight strata measured, the radium content of Chattanooga Shale was 20-fold higher than that of any other stratum. There is a layer of bedrock above the shale and below the studied houses that is approximately 500 feet thick. If we assume that Chattanooga Shale is the source of most of the radon found in the studied houses, then it has migrated a substantial distance to reach these houses.

VI. Summary

Vehicle-mounted radiological equipment can be used in a variety of ways to identify and diagnose houses with radon problems. Some of the capabilities can be duplicated using modern portable electronic devices, but not all. In some cases the presence of a vehicle is needed due to the weight of shielding required or the presence of generators, computers, and other equipment for more sophisticated analyses.

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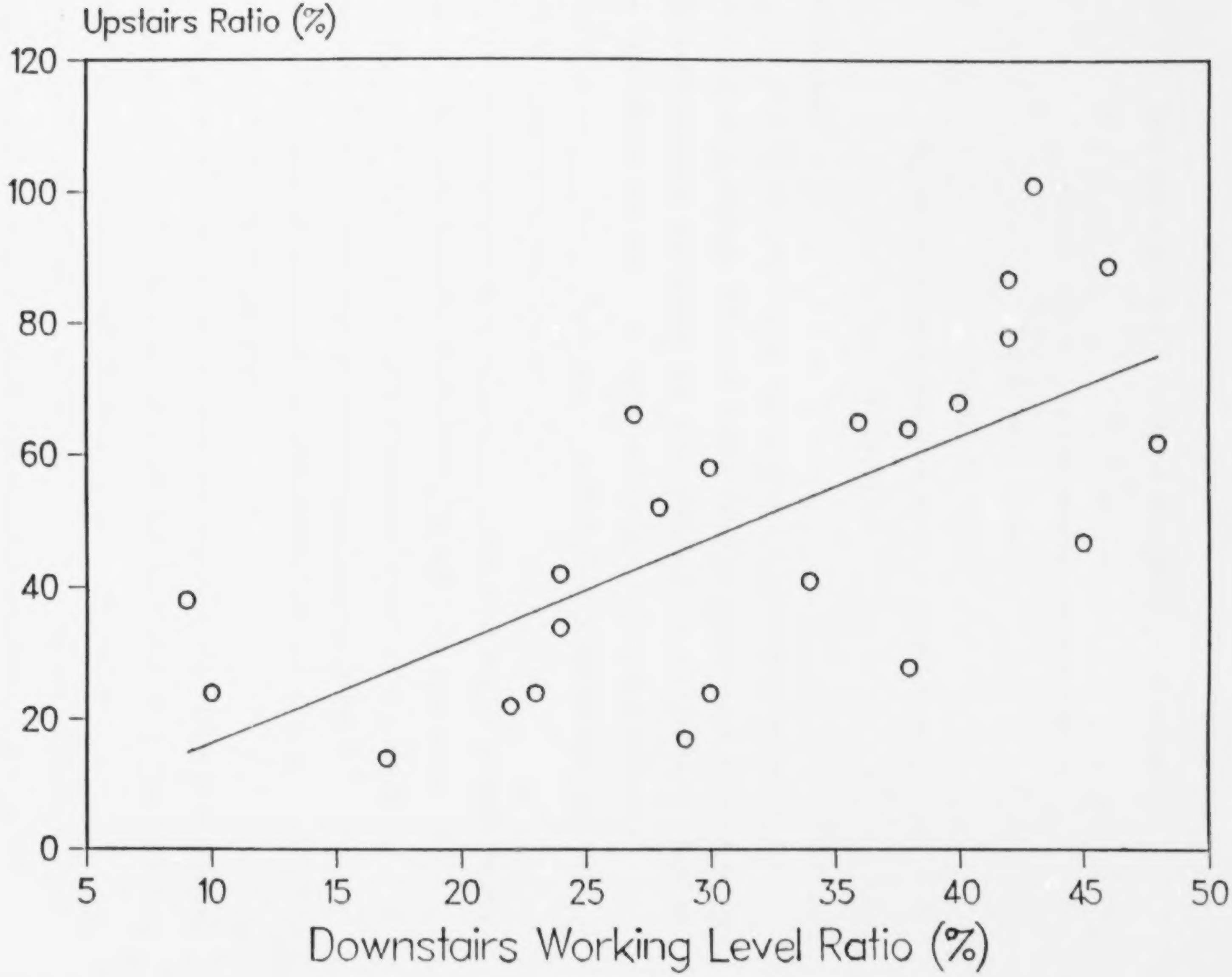
Upstairs equilibrium ratios tend to be 55% greater than downstairs.



Soil Characterization for Radon Availability and Transport

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Introduction

To identify high risk areas and to gain a better understanding of the causes for above average levels of indoor radon it is necessary to characterize the surficial soils and bedrock for radon availability and transport. Some of the measurements and measuring techniques we have used to determine the availability and transport of radon in surficial soils and bedrock will be briefly discussed in this report.

The availability of radon refers to the rate of formation of radon in the gaseous state (soil gas) that is available for transport into homes. The availability is related to the soil and bedrock radium concentration, the emanating fraction, soil porosity and soil gas radon concentration. The transport of radon is related to the permeability (inverse of resistance) of the soils and bedrock for gas flow.

There is existing information available regarding the radium concentration and permeability of the surficial soils and bedrock. Most of the U.S. has been mapped for surficial γ through the National Airbourne Radiometric Reconnaissance study conducted by the DOE as part of the National Uranium Resource Evaluation program. These airbourne NaI measurements observe γ radiation from about the first foot of surficial soil or rock. Latitudinal and longitudinal flight lines were spaced 3-6 miles and 12-18 miles respectively. These data should be useful in identifying regions high in surficial radium.

Information from mining and drilling operations is also useful in locating areas high in bedrock uranium and radium.

For most of the United States there is a great deal of information available with regard to soil type, depth, water permeability, particle size and bedrock. Most of the soil information can be obtained from soil conservation service data. Maps of the surficial bedrock geology are also available in addition to soil, ground water and bedrock data from sources such as drilling logs. As the understanding of the relationship of soil gas permeability and indoor radon improves the available surficial soil and bedrock information will be of great value in identifying potentially high risk areas.

Surficial Gamma

Surficial gamma measurements were made using NaI survey meters by placing the meters directly on the ground. In addition to measuring the γ flux from radionuclides in the ground the meters were sensitive to cosmic rays. Long Island soils with geometric means for U-238, Th-232, Ra-226 and K-40 of 0.9, 0.8, 0.6 and 6.9 respectively averaged 9 μR/hr at the surface. Of this about 3μ R/hr can be attributed to cosmic rays. Shallow soils over black shade in Onondoga County with geometric means for U-238, Th-232, Ra-226 and K-40 of 2.7, 1.1, 2.3 and 26.7 respectively averaged 14 μR/hr at the surface. We have found that surficial gamma measurements are easily made and are a good indicator of surficial soil and bedrock with above average concentrations of Ra-226. It is possible that high surficial gamma readings are due to above average concentration of U-238, and/or Th-232, and/or K-40 in soils or rocks with normal concentrations of Ra-226, however, in general this is not the case.

Soil Ra-226

Soil samples of about 1 kgm were usually collected from depths between 2 to 4ft. Occasionally soil profiles were measured by taking samples at every foot down to 4 feet. The samples were sealed in plastic bags and returned to the laboratory for analysis. The soils were dried at 100°C, the moisture content determined, and then passed through a 20 mesh sieve (.841 mm opening). The gamma spectrum of the fraction passing through the sieve was measured using either Ge(Li) or NaI detectors. Rock samples were broken and passed through the same 20 mesh sieve. Samples of about 70 gm were sealed in plastic bottles for GeLi counting and about 300 gm were sealed in Al cans for NaI counting. A radon-radon daughter in growth period of 3 weeks in the sealed containor was allowed before counting. In addition to Ra-226, the concentration of U-238, Th-232 and K-40 were routinely measured.

Portable γ spectroscopy equipment is available and would be very useful for field measurements of Ra-226.

Soil Gas Rn-222

The concentration of radon in soil gas was measured using both grab sampling and time integrating techniques. Grab samples were taken by driving a 1/2" diameter pipe into the soil at depths ranging from 1 to 4 ft. (Figure 1). The end of the pipe was fitted with a driving point and perforated with about 50 small holes (3/32" diameter). The pipe was attached to a diaphram pump and air withdrawn at 200 cc/min for 5 min to purge the pipe and lines. A 1-liter evacuated flask was then filled with soil gas and returned to the laboratory for Rn-222 measurement using Lucas scintillation cells. Samples were also measured in the field by flushing scintillation cells with soil gas and counting with portable photomultiplier equipment. Samples were generally taken at depths of 2 and 4 ft. The average Rn concentration in soil gas at 4' was about a factor of 2 greater than observed for samples taken at 2'.

Soil gas radon measurements were also made using alpha track detectors (Figure 2). Time integrated measurements were made for periods ranging from a few weeks to several months. A 6 in. hole was augered or dug to depths ranging from 2 to 4 ft. A three-inch diameter PVC pipe with a reducing fitting on one end was placed in the hole and the soil tamped into the space around the pipe. A 1 1/2-in. diameter PVC pipe with a track etch detector attached to the end is then placed inside the 3 in pipe and threading into the reducing fitting. The 3 in pipe is left in the ground and the alpha track detector periodically changed by withdrawing the inside pipe. Alpha track detectors with membranes to exclude thoron are used for soil gas measurements of Rn-222.

Permeability

The permeability of the soils for gas flow is measured with the apparatus used to take grab samples of soil gas (Figure 1). Soil gas is withdrawn using the 1/2 in diameter soil pipe at a measured rate of 200 cc/min. The pressure differential, P (atmospheric) - P (line), required to maintain the flow is also measured using either a pressure differential transducer or magnehelic pressure gauges. The gas flow permeability is then calculated using a relationship reported in "Review of Existing Instrumentation and Evaluation of Possibilities for Research and Development of Instrumentation to Determine Future Levels of Radon at a Proposed Building Site" by DSMA Atcon Ltd., January 1983.

$$k = 2.5 \times 10^{-7} \frac{Q}{P}$$

where $Q = 1/\text{min}$

$P = \text{cm of water}$

$K = \text{cm}^2$

Permeability measurements were generally made at depths of 2′ and 4′. Water, bedrock or changes in soil type often caused the permeability to change considerably with depth.

Sample Collection

In our study samples of soil and soil gas and permeability measurements were generally taken at depths of 2 and 4 ft., and at distances of about 1 1/2 ft. and > 20 ft. from the basement wall (Figure 3). To more adequately characterize the soil as it relates to radon entry into homes, measurements should be made to depths of 6 ft. when possible. For homes with basements, a soil depth of 6 ft. would normally be about 1 ft. below the basement floor. Profiles with sampling at depths of 2, 4, and 6 ft. would more adequately characterize the soil volume that contributes most to the soil gas radon entering homes. Samples taken from beneath the basement floor from sumps, floor drains, wall interiors, etc. relate directly to measurements made in the soil around the house.

Tracer Studies

A passive perfluorocarbon tracer technique developed at Brookhaven National Laboratory was used to make in house multizone air infiltration analyses. Perfluorocarbon tracers were also placed in the soil near homes and the fraction of emitted gas that entered the house was measured. The tracer sources were placed in the PVC soil pipes in the same position as the alpha-track detectors (Figure 2). Tracer gas sources were placed in the PVC soil pipes located 1 1/2 ft. from the foundation at depths ranging from 2 to 4 ft. Tests conducted at 45 homes showed that, on average, 55% of the emitted tracer actually entered the houses. Five different tracer gases are available and could be placed at various locations in the soil around or under a home to study the flow of soil gas into homes. These measurements can be integrated over time period ranging from about 6 hrs to several months.

The work described in this paper was not funded by the U.S. Environmental Protection Agency. The contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

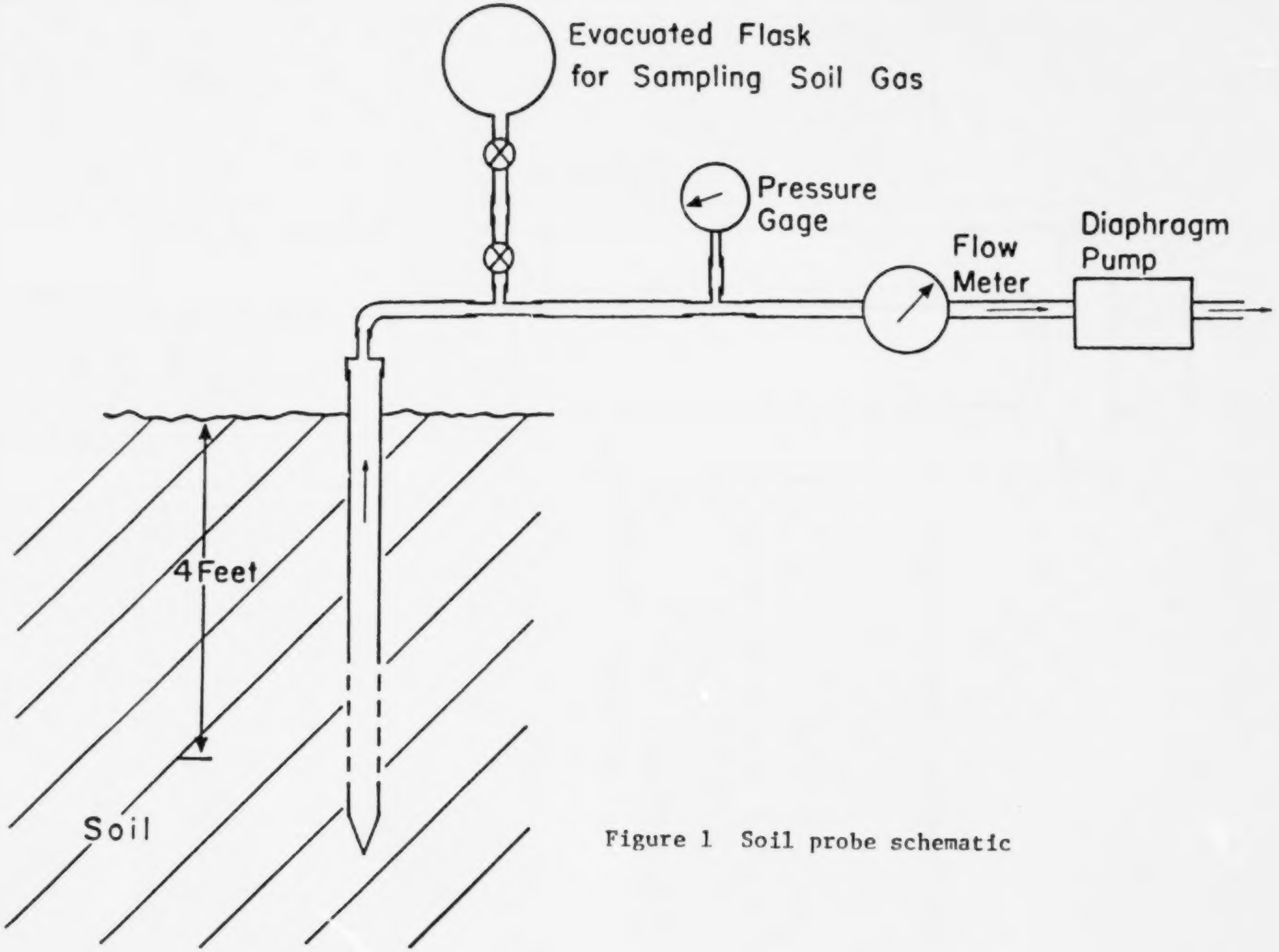
Evacuated Flask
for Sampling Soil Gas
Pressure
Gage
Flow
Meter
Diaphragm
Pump
4 Feet
Soil

Figure 1 Soil probe schematic

SOIL GAS RADON-ALPHA TRACK MEASUREMENTS

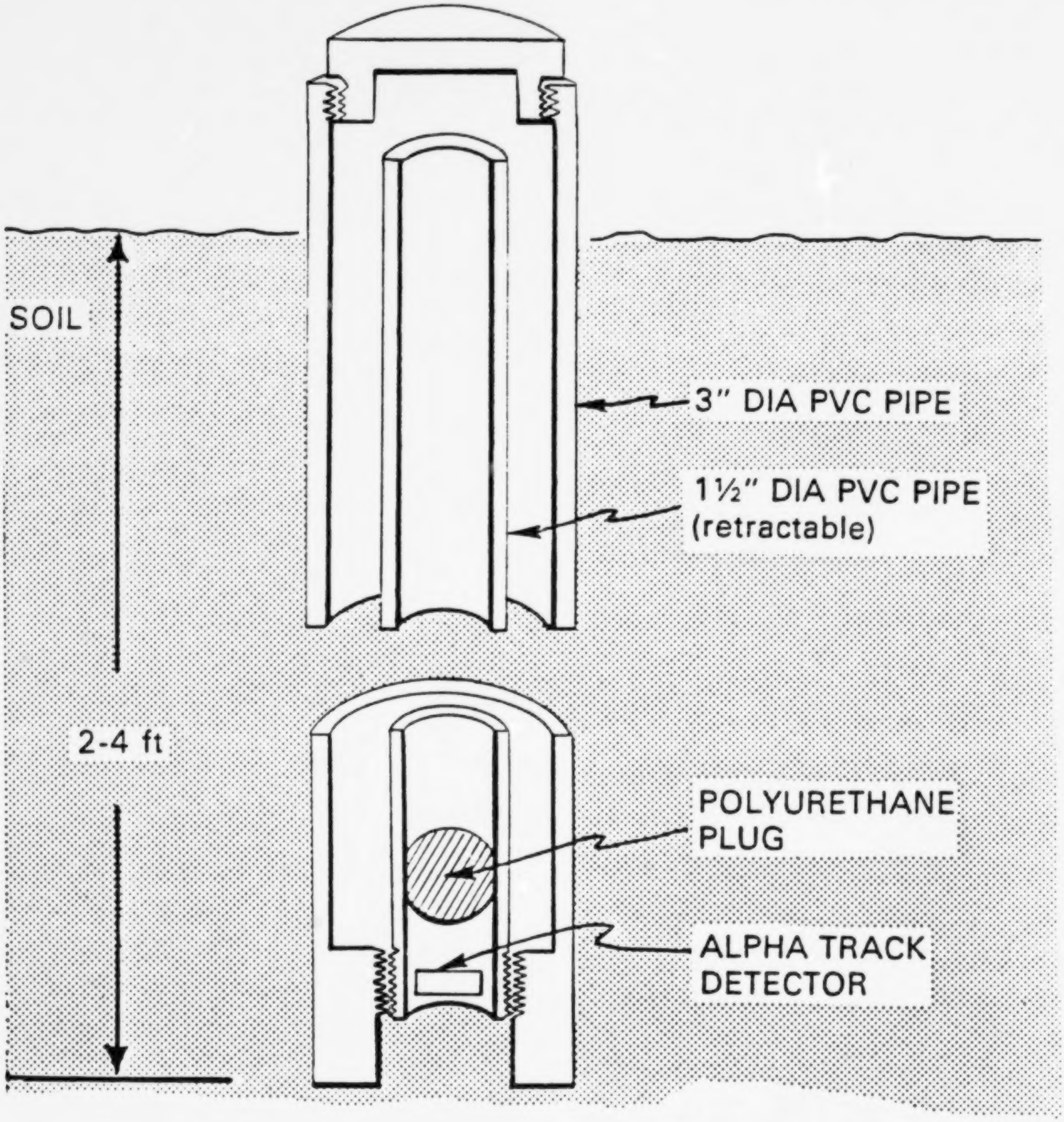
SOIL
3" DIA PVC PIPE
1½" DIA PVC PIPE
(retractable)
2-4 ft
POLYURETHANE
PLUG
ALPHA TRACK
DETECTOR

Figure 2 Detector placement in the soil

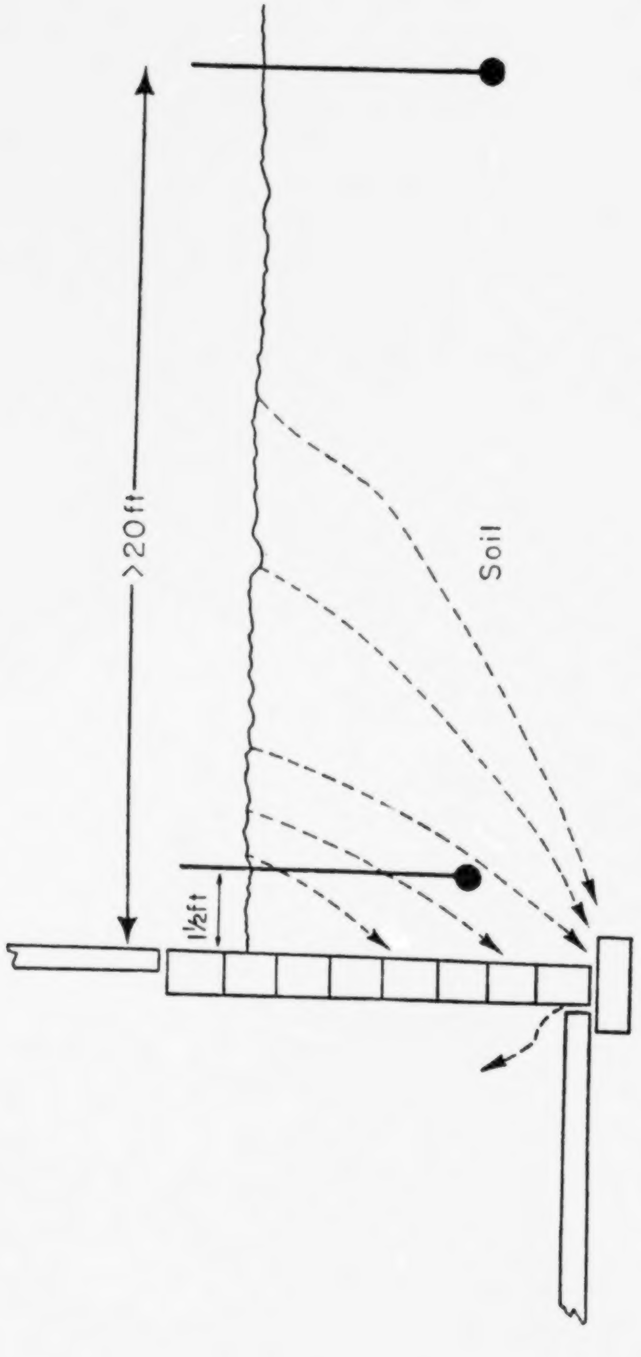
>20ft
1½ft
Soil

Figure 3 Locations of soil permeability measurements

The work described in this paper was not funded by the U.S. Environmental Protection Agency. The contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

OVERVIEW OF SELECTING RADON MITIGATION METHODS

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Over the past several years a growing number of researchers and contractors have been lowering elevated radon levels in residences by a number of techniques. All of them fit into one of the following categories:

1) Prevent radon entry

- preventing radon entry by soil depressurization or pressurization
- preventing radon entry by basement pressurization
- preventing radon entry by sealing of entries

2) Dilution of radon by introducing outside air (It is important that this does not increase soil entry by putting negative pressure on the basement)

- heat recovery balanced flow
- non-heat recovery flow (Blowing in or powered by negative pressure on the basement)

There are perhaps a dozen specific methods that have been tried with varying degrees of success in lowering radon concentrations and no doubt several more that are experimental, untried or undreamed of. The advantage to having a number of techniques available to choose from is that it gives flexibility - an opportunity to use a method that has a greater chance of success.

The problem of course is to select the one or two from amoung the multitude that gives you greater chance of success or is most appropriate for the situation.

Here are my thoughts on selecting a mitigation technique, based on experience, feelings, the work of many others and of course analysis of the physics involved. Please keep them in perspective. In many ways they are incomplete or tentative. They are certainly open to new thought and modification. I would be very distressed if they interfered with new insight or discouraged asking questions by appearing to provide answers when they are really ideas.

Begin at the House

Probably 80% of the information I use to decide on a mitigation technique is gathered by using my eyes and brain while visiting the house. First thing I do is see what state of mind the homeowner is in. I may be the first semi-knowledgeable person to come in contact with them and they may have a number of fears concerning their health, their families health (will this affect my daughter's ability to have children ?) and the impact on the value of the property. I want to keep them from undue panic but not calm them down so much that they don't do something about a real problem.

The second thing I do is get a feeling for the house by walking around it keeping my mind clear and paying attention to my peripheral vision. I'm looking for how the building's put together, are there any unaccounted for volumes in the house, exhaust fans, furnaces, ways to get pipes around. But most importantly I'm looking for ways that radon can enter the building, how does the building hit the ground, sumps, footer drains, crawlspaces,any place there is a large soil surface that has good airflow connection to the house.

I am always asking "What is going on here ?" Where is radon coming in ? Why is it coming in at all ?

Then I make a floorplan and fill out the site form. This is nothing more than a way to get the information most critical to selection of a mitigation plan together in one spot. The homeowner may know if there are exterior footer drains, perhaps there are gutters emptying into risers from the footer drains and you can see them. The homeowner may have photographs of the building under construction from which you can learn a great deal. Once again it is physical inspection that tells you most.

Look and see !!

The key things I look for when simply observing are:

For soil depressurization

- soil gas entry points using eyes and smoke sticks
- anything that is like a cavity that has a large contact with soil surface
    - hollow core block walls, cored and reinforced ?
    - interior or exterior footer drains
    - sump holes (drains or not?)

For basement pressurization

- basement that seems tight and is easily isolated from the upstairs
- no combustion appliances upstairs
- basement that is hard to apply soil depressurization to (finished, hard to seal wall or slab openings)

For dilution with outside air

- crawlspace or basement that is easy to isolate (no freeze problems, few penetrations)
- tight house
- lack of other options

Measurements

Soil Depressurization Tests

Drill at least two holes through the slab (basement floor, slab on grade or crawlspace floor). One of these is 1-1/4" diameter (coincidentally the O.D. of the hose for a Eureka Mighty Mite vacuum cleaner), the other 3/8".

Use smoke sticks to see if soil gas is entering from the holes (if it is then the make up air must be coming from somewhere, eh?

Look in the large hole. What do you see ? #2 stone, sand and gravel, silt, clay, bedrock ? A good bed of stone everywhere and you can easily depressurize the entire sub-slab soil surface (maybe 1800 square feet or so in one fell suction point).If it is clay it will be hard to get any pressure field to develop under the slab. If the soil has settled away from the slab (most likely near the edge) you may have good access to a large soil surface even if the sub-slab soil is clay.

If the basement wall is concrete block drill at least one 3/8" hole in it. If there is a wall that has a slab on grade next to it (like a garage floor, a patio or living area as in a split level design) then drill a 3'8" hole in that and one hole in another wall.

Take a grab sample under the slab and in holes in the block walls (or better yet do a sniff with a scintilation flask). Are they higher than the basement air ? Are they higher because it is a major source or because the air under the slab is very stagnant ? This is one of the tests I'm not sure how to interpret. Does it really make a difference if I depressurize the soil in the location with the highest concentration ? I am sort of using that as a guideline right now, but I wish someone would do some research to help me understand grab sample results better.

Use the vacuum cleaner to put a suction on the large hole in the slab and check with smoke sticks at the other holes that you've drilled through the slab and walls or at floor cracks, sump holes and other openings through the slab that were already present to see how easily air will move beneath the slab. If there is #2 stone or a cavity under the slab this will probably be quite far. If it is sand under the slab you can expect a pressure field to develop only 5 to 15 feet away from the suction point. Sometimes in a very fine, tightly packed soil (fine sand or silt) you will get no airflow with this test, but if you release some Freon under the slab at one of the smaller holes it will quickly move to the vacuum where it can be detected in the vacuum exhaust with a halogen detector of the type used by refrigeration and air conditioning technicians. With the vacuum cleaner not running you can inject Freon under the slab and find locations where it leaks back into the basement, identifying soil gas entry routes, and if exterior footer drains are present you can sometimes find where they drain away to daylight by sniffing around outside and finding Freon exiting to the open air.

The purpose of these tests are to decide whether soil depressurization can be effectively employed as a mitigation technique. If it is easy to develop a pressure field in the sub-slab agregate or block wall then this will be a preferred method. If the vacuum cleaner test results show no airflow but Freon will move or if the vacuum cleaner suction test ios marginal (spotty or only a few feet) then sub-slab suction might be possible but should be considered with other possibilities.

Basement Pressurization

A fan door test between the basement and upstairs is done with particular attention paid to the 10 Pascals or less delta P range. The test should be run so that air is being blown from the upstairs into the basement. In the basement another person is checking with smoke sticks to see when soil gas stops entering the building, reverses and is actually leaving the basement and being blown back out into the soil creating a sort of air pressure shield that forces soil gas away from and around the building. If this can be accomplished using a small enough airflow (I'd say less than 300 cfm at 10 Pascals) then basement pressuriztion may be considered as a mitigation tehcnique. In this method air would be drawn from the upstairs house putting some negative pressure on the upper part of the building and blown into the basement to pressurize it and prevent soil gas entry. The fan door test will give you some idea of what performance characteristics a fan would need to do the job. If the airflow rate can be lowered from 300 cfm to 200 cfm by sealing the floor between the basement and the upstairs then this should not greatly add to the energy load from infiltration because it is just reversing the normal stack effect airflow found in cool climates in the winter time. Another precondition for this mehtod would be the absence of a fireplace, woodstove or other vented combustion device in the upstairs where the pressurization air would be drawn from.

Dilution of Radon Test

A fan door test is done on the whole house to get an idea of how tight the building is. This will aid in deciding if introducing dilution air is a possibilty for controlling radon levels. Armed with some simple infiltration models and assuming that dilution air can be added without putting a negative pressure on the house that would increase soil gas entry an estimate can be made of the expected reductions in radon concentrations for varying increases in ventilation air.

If there is a crawlspace or basement that would be easy to isolate from livingspace and does not contain things that would need freeze protection (or are easily protected from freezing) then I would consider isolation of the space and passive ventilation (followed by active ventilation if passive didn't quite do it).

Selecting The Mitigation Technique

When it comes to selecting a mitigation method I am currently using the following order of preference.

- soil depressurization (or pressurization)
- basement pressurization
- isolate and ventilate (crawlspace or basement)
- ventilate house

For deciding on what do do within each of these categories I am using logic shown in the decision charts for each of these categories at the end of this paper.

All of this is just used as guidelines and the final selection will involve aesthetics, noise, homeowner preference, budget, insight from the mitigation contractor, permanence of installation, power consumption, longevity and a variety of other more or less subjective factors that may overide the logic outlined above.

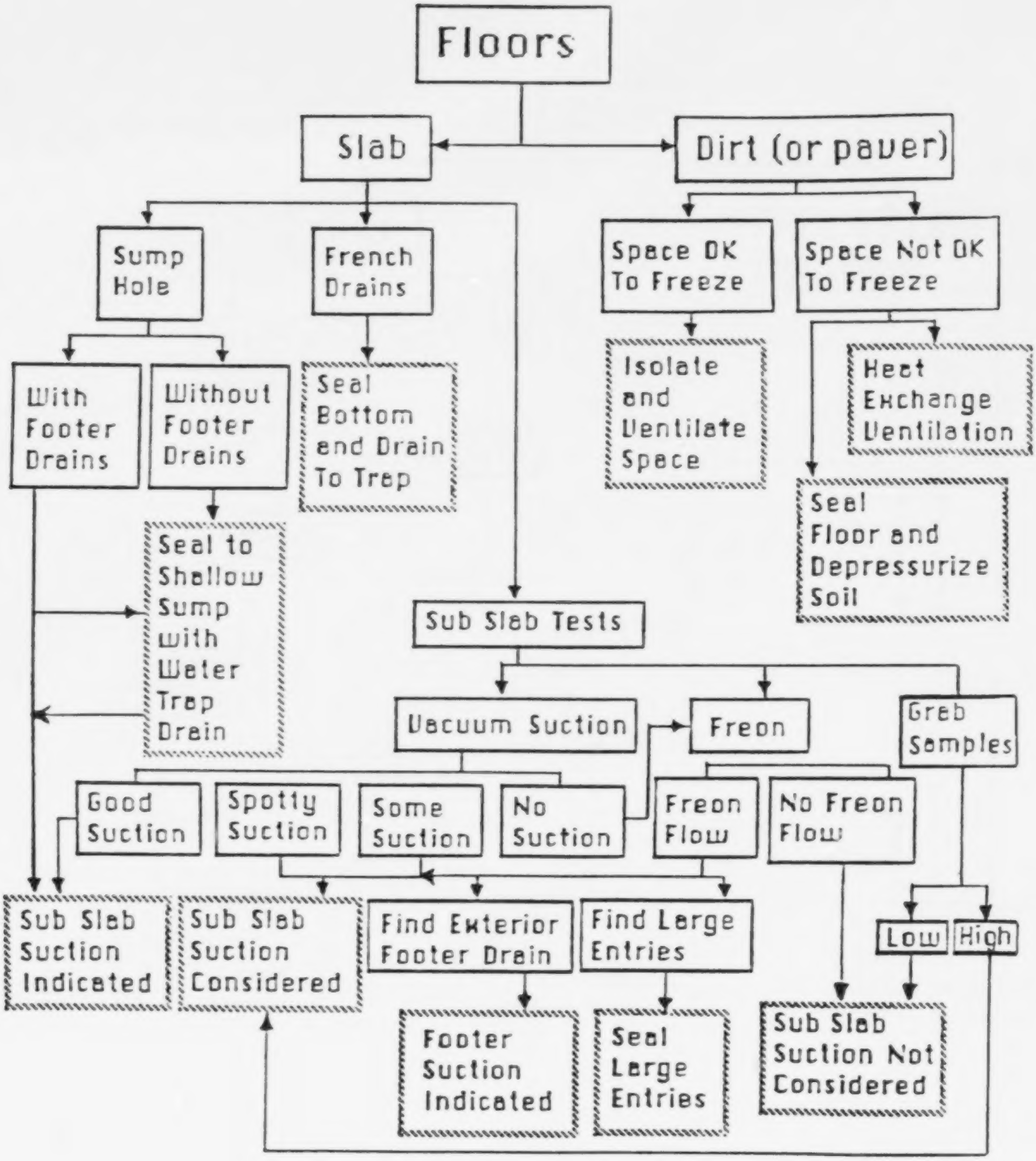
A series of figures that summarize this discussion, including flow diagram and summary sheets, are supplied on the pages that follow.

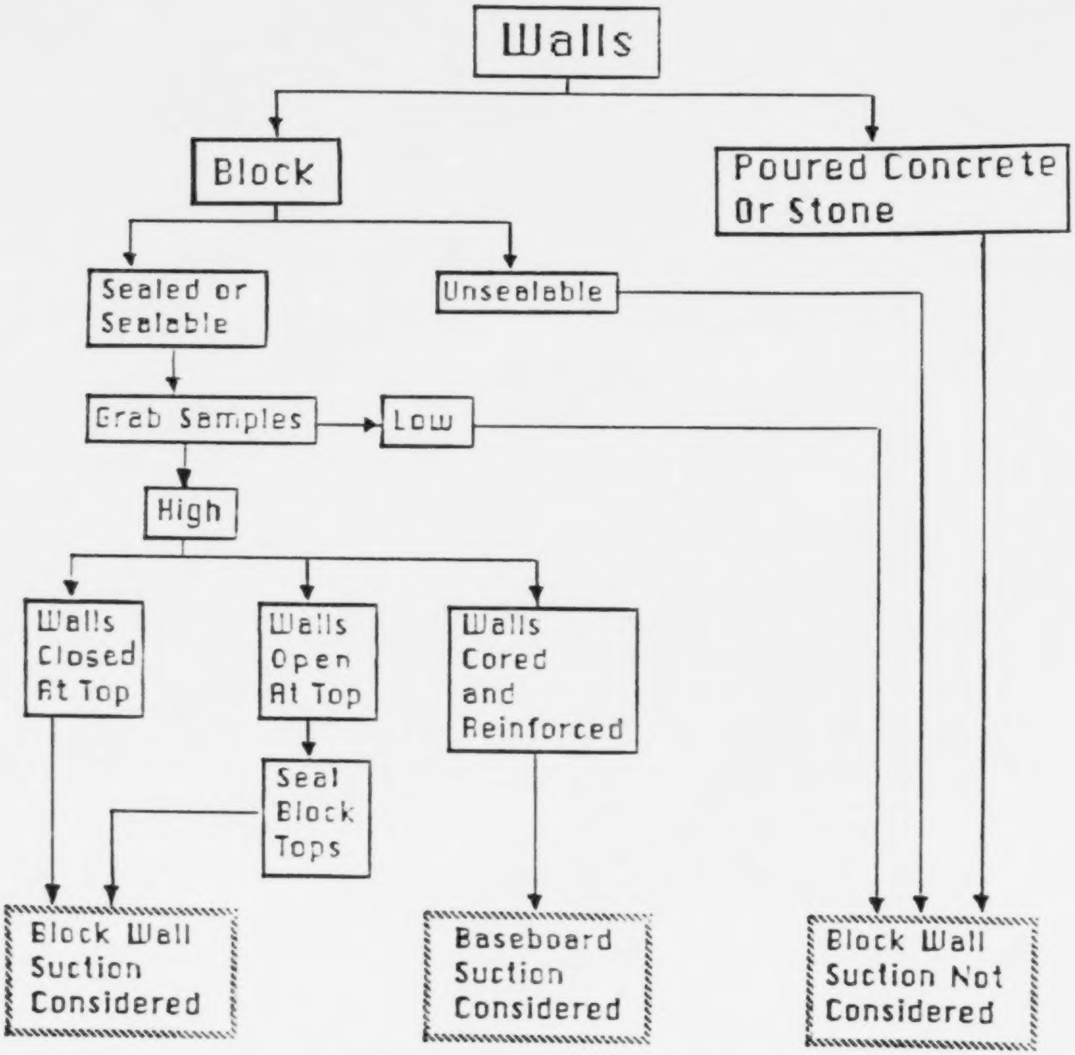
Selecting Mitigation Method

Investigate Building by
looking, filling out site forms,
doing qualitative and quantitative
tests.

Use Results of Tests and
Flowcharts to make a List
of Mitigation Techniques to
be Considered

Make the Final Selection Based
on Your Current Method Prioritization
List and all Those Important Factors
That Flowcharts Don't Accomodate
Aesthetics, Noise, Homeowner
Preference, Contractor Input,
Combinations of House Features
That the Charts Don't Allow.


Floors
Slab
Dirt (or paver)
Sump Hole
French Drains
Space OK To Freeze
Space Not OK To Freeze
With Footer Drains
Without Footer Drains
Seal Bottom and Drain To Trap
Isolate and Ventilate Space
Heat Exchange Ventilation
Seal Floor and Depressurize Soil
Seal to Shallow Sump with Water Trap Drain
Sub Slab Tests
Vacuum Suction
Freon
Grab Samples
Good Suction
Spotty Suction
Some Suction
No Suction
Freon Flow
No Freon Flow
Low
High
Sub Slab Suction Indicated
Sub Slab Suction Considered
Find Exterior Footer Drain
Find Large Entries
Footer Suction Indicated
Seal Large Entries
Sub Slab Suction Not Considered


Walls
Block
Poured Concrete Or Stone
Sealed or Sealable
Unsealable
Grab Samples
Low
High
Walls Closed At Top
Walls Open At Top
Walls Cored and Reinforced
Seal Block Tops
Block Wall Suction Considered
Baseboard Suction Considered
Block Wall Suction Not Considered

Current Prioritization List

My current order of preference for mitigation techniques is as follows :

- Depressurize soil or isolate and vent non-living spaces (use flowcharts for Walls and Floors to find which methods should be considered for the house)

- Pressurize basement (Do a fan pressurization test on the basement using the basement door to decide if this is appropriate and if so what fan flow at what pressure drop is needed. Currently, I'm using 300 cfm as the decision point)

- Add ventilation air to dilute the radon (Use a fan, test on the whole house to help decide if adding dilution air will provide the reductions needed assuming that it can be done with balanced or positive pressure flow).

HOUSE SUMMARY SHEET

HOUSE ID ____________ PHONE NUMBER ________________________

NAME ____

ADDRESS ____

____

____

HOUSE TYPE ____

HOUSE AGE ____________________

TIGHTNESS DATA

AIR CHANGES AT 50 PA ______________________ ELA _______

EARTH CONTACT AREAS

_____ PIERS ____

_____ SLAB ____

_____ CRAWLSPACE ____

_____ BASEMENT ____

SOIL GAS ENTRY ROUTES

_____ CRACKS IN WALL _____ SUMP HOLE w/DRAIN TILE

_____ CRACKS IN SLAB _____ AIR DUCTS UNDER SLAB

_____ EXPOSED EARTH _____ OPEN CONCRETE BLOCKS

OTHER ENTRIES

____

____

____

____

HOUSE SUMMARY SHEET - PAGE 2

NEGATIVE PRESSURE DATA

Exhaust Devices

CFM

_____ Bath Fans _____ ____________________

_____ Dryer _____ ____________________

_____ Range Fans _____ ____________________

_____ Kitchen Fans _____ ____________________

_____ Whole House Fan _____ ____________________

Heating System Type

Fuel _________ Distribution ____________________

Thermal Bypasses

_____ Around Chimney

_____ Balloon Walls

_____ Soffits

_____ Attic Scuttle

_____ Plumbing Chase

_____ Recessed Lights

_____ Bath Fans

_____ Pocket Doors

Other Bypasses ____________________________________

____

____

____

RADON MEASUREMENT HISTORY

Time Integrated

Date	Location	Results	Units

HOUSE SUMMARY SHEET - PAGE 3

Grab Samples

Date	Location	Results	Units

Suggested Mitigation Strategies:

FLOOR PLAN

HOUSE ID:

HOUSE ID:	LOCATION:	NOTES:
FLOOR PLAN	TECHNICIAN:	
	DATE:	

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

INTERIM REPORT ON DIAGNOSTIC PROCEDURES FOR RADON CONTROL

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(Editor's Note: The following pages are an abstract of the report, EPA-600/8-88-084 (NTIS PB88-225115), June 1988, not available at the time of the Workshop.)

I. INTRODUCTION

With the discovery of high indoor radon (Rn-222) concentrations in a significant number of residences since the late 1970's, it has become important to develop a better understanding of the mechanisms of radon movement into and accumulation in buildings and suitable methods for controlling or eliminating the accumulations. In general, earlier research has found that the most significant source of indoor radon is the soil surrounding the building shell from which radon migrates into the building transported by pressure-driven flow of soil gas. A few of the factors influencing the radon entry rate include indoor-outdoor air temperature differences, wind loading, soil characteristics, construction details of the building superstructure and substructure, and coupling between the soil and the substructure.

In order to further investigate radon entry and radon control techniques, the U.S. Environmental Protection Agency (EPA), the Department of Energy (DOE), and the New Jersey Department of Environmental Protection (NJDEP) are funding an intensive study in fourteen northern New Jersey homes. The research is being conducted by the Lawrence Berkeley Laboratory (LBL) in seven homes and collaboratively by Oak Ridge National Laboratory and Princeton University in a second set of seven homes. Since few studies have attempted to relate influencing factors to entry rates and to investigate the importance of these factors on systems designed for radon abatement, the following overall objectives were established for this project.

- Extend our understanding of the fundamentals of soil gas flow and radon entry into buildings and improve our basic knowledge of factors that influence the entry rate.
- Develop a better understanding of the success or failure of certain mitigation techniques and of the operational ranges of key parameters that affect the utility of these techniques.
- Refine and develop analysis procedures for diagnosing radon entry mechanisms and the selection of appropriate control systems.

The basic research plan for this project has four main operational components: 1) house and site characterization measurements, 2) baseline and continuous monitoring of environmental and building parameters, 3) diagnostic procedure development, and 4) installation and operation of selected mitigation techniques.

This report focuses primarily on item 3, development of diagnostic procedures. Diagnostic procedures are defined here as an organized and logical set of measurements, tests, and observations that are necessary for identifying the specific means by which radon enters and accumulates in a particular structure. In addition, these procedures should point the way to a suitable system or technique for controlling the indoor radon levels. These procedures may also encompass follow-up measurements, tests, and observations important in optimizing mitigation system performance. This development effort builds on the previous, on-going, and generally unpublished work of others, including Scott, Tappan, Henschel, Ericson, and Brennan, as well as on the basic scientific understanding developed by Nazaroff, Nero, and others at LBL. Hopefully, it provides a format for refinement, reduction and interpretation of the measurements and observations necessary for selecting an appropriately designed, effective, and economical system for controlling indoor radon levels in a majority of existing U.S. single-family houses with elevated radon concentrations.

TABLE 1: Project Measurement Activities

1) Parameters to be monitored continuously:

    - indoor radon concentrations (various locations within the house), and possibly radon progeny concentrations (smaller subset of houses),
    - outdoor and indoor temperatures,
    - meteorological parameters at each site, including windspeed and direction,
    - pressure differentials across the building shell (various locations),
    - soil moisture and temperature, and
    - barometric pressure and precipitation at one central site.

2) Parameters to be monitored periodically:

    - soil air permeability,
    - ventilation rate,
    - indoor water vapor,
    - soil gas radon concentrations at selected locations, and
    - occupant effects and activities, including operation of a fireplace or wood stove, forced air furnace systems, exhaust fans, *etc*.

3) Parameters to be measured once or occasionally:

    - effective leakage area,
    - radon progeny concentrations,
    - soil characteristics (at LBL), including permeability, grain size distribution, soil radium concentration, and emanation ratio,
    - frost depth and snow cover,
    - pressure-field mapping to determine coupling between building shell and surrounding soil,
    - tracer gas (SF_6) injection in soil and resulting concentrations within the building shell (if utilized), and
    - additional parameters specific to the mitigation technique under investigation, such as the flow rate of air through a block wall or subslab ventilation system, or tracer gas analysis of flow pathways.

II. OUTLINE OF GENERAL DIAGNOSTIC PROCEDURES

The premise for much of the diagnostic procedures developed and discussed here is that the pressure-driven flow of radon-bearing soil gas is the most significant source of radon in houses with elevated concentrations. While further discussion of this premise is beyond the scope of this report, the reader should refer to DSMA, (1985) and Nazaroff, *et al.*, (1985a, 1985b, 1986) for additional discussion. On the other hand, other potential sources of radon, such as water and building materials, are also included in the diagnostic procedures discussed here. A good overall review is found in Nero and Nazaroff, (1984).

The procedures described here rely on a series of individual site-specific observations and measurements of air flow, pressure differentials, radon concentrations and near-building material characteristics. This collection of measurements is then used to identify primary radon sources (water, building materials, soil) and most probable radon entry points and mechanisms. Various tools and instruments (see Table 2) are necessary to conduct the diagnostic procedures discussed here and this report assumes that the reader has prior experience with flow and pressure measuring devices, and alpha particle counting techniques. Samples of forms for recording this diagnostic information are found in Appendices A, B, C, D and are referred to in the text.

Some investigators have used gamma radiation surveys as a method of locating radon source materials. Making and interpreting results of such surveys in buildings appears to pose a number of difficulties and we have not utilized this technique here. Since soil gas flows are the most significant source of radon in houses, the location and extent of penetrations through the building shell, along with physical characteristics of the surrounding soil (such as air permeability) are the most important determinants of radon entry and source locatoin. Variations of apparent radium and/or radon concentration in the soil near the building may not be correlated with entry locations. The methods we discuss here, particularly air sampling for radon at suspected entry points and in areas where radon accumulation is likely, provides a more direct method of identifying radon sources and entry locations.

Radon, not radon progeny, is measured before, during, and after diagnostics and is the contaminant on which control efforts are focussed. In its role as progenitor, control of radon also controls radon decay products, which are responsible for the adverse health risks associated with radon exposures. There are some potential mitigation measures directed at progeny control only, such as air cleaning. These are not considered here.

Before diagnostic procedures for radon control are employed, the indoor radon concentrations on any occupied floor in a particular structure should be verified during the heating seasons as being greater than the recognized guideline. Methods and procedures for determining indoor radon concentrations during non-heating season periods are being studied. However, relationships between heating season and non-heating season concentrations in homes with elevated concentrations have not been established. In this report, EPA's suggested guideline of 4 pCi/L annual-average concentration is used as a conservative heating season worst case target in diagnosis and in determination of successful mitigation. Ultimately, these heating season measurements would predict the annual average concentration. However, at this time, we are unable to make that prediction. The basic procedure here can be used with different guidelines. For example, in an area with many homes with indoor concentrations greater than 20 pCi/L, these houses might be the main objective of diagnostic and remedial efforts during the next several years.

TABLE 2: Instruments and Equipment

Radon Grab Sampling:	Alpha scintillation cells
	Portable photomultiplier tube counting station
	Hand pump with sample tube and 0.8 μm filter
	Compressed air or nitrogen for cell flushing
	Vacuum pump for evacuating cells (70 cm, 27 in. Hg vacuum)
Air Leakage and Flow Measurements:	Calibrated-flow blower door (6800 m^3h^{-1}, 4000 cfm @ 5 Pa)
	Pitot tubes (electronic or liquid-filled manometers: 1-50 kPa)
	Hot wire anemometer (with temperature sensing element)
	Smoke tubes
	Industrial vacuum cleaner (170 m^3h^{-1}, 100 cfm @ 2m, 80 in. H_2O pressure)
	1.5 m (5 ft.) flow sections of : 7.6 cm (3 in.) PVC with coupler 15 cm (6 in.) galvanized duct
	Non-toxic tracer gas (SF_6, Freon 12)
	Tracer gas detection instrument
Soils Characterization:	Soil core and auger samplers
	3/4" reversible electric drill
	Soil air permeability device
	Sliding hammers
	Various diameter drill bits, including some attached 1.5 m (5 ft.) long extensions
	1.5m (5 ft.) long probe pipes
Inspection Equipment:	Stiff wires
	Telescoping mirrors
	Portable gamma spectrometer
	Fiber optics scope
Tools:	3/8" variable speed hand drill
	Masonry bits
	1/2" hammer drill
	Impact bits
	Pocket flashlights
	Hand sledge
	Pry bar
	Pipe wrench
	Locking pliers
	Adjustable wrenches
	Portable lights
	Step ladders
	Long blade screwdriver
Miscellaneous:	Forms
	Inspection hole plugs
	Epoxy-based mortar patch or hydraulic cement
	Duct tape
	Duct seal
	0.3, 0.6, 1 cm (1/8, 1/4, 3/8 in.) diameter tubing
	Various-sized hypodermic needles
	Plastic film
	Thermometers: electronic and mercury-filled glass
	Silicone sealant

III. DISCUSSION OF DETAILED DIAGNOSTIC PROCEDURES

A "General Plan for Radon Control", shown in Figure 1, outlines the basic process for mitigating elevated radon levels. Once a structure is determined to have a radon problem, a survey of the structure is conducted that characterizes soil-linked radon entry points in the building shell and evaluates potential non-soil sources. After reviewing the results of the diagnostic measurements, suitable options for radon mitigation are considered and a final plan for the control system(s) is developed. Follow-up measurements of indoor air concentrations and system operating conditions are made once the installations are completed. If follow-up short-term diagnostic measurements of indoor radon concentrations are still greater than the guideline, then modifications or additional system options must be installed. For apparently successful installations, the system is tuned for improved efficiency (*i.e.*, effective performance with reduction in system size requirements) and more economical operation and the reduced indoor levels are verified with a 14-day average heating season measurement.

The report discusses details of the various diagnostic methods, techniques, and procedures currently under development. Figures 2-7 in flowchart-graphical form show a logical sequence of steps that will assist in guiding the reader through the measurement and evaluation process. We emphasize again that this system of diagnosis is for research purposes and is intended to serve as the basis of somewhat simpler approaches for general application.

IV. SUMMARY

A preliminary set of diagnostic procedures has been developed for identifying the sources of indoor radon problems and selecting systems for controlling radon. In the homes where the recommended remedial measures have been installed, based on the diagnostic measurements, radon concentrations have fallen below the guideline of 4 pCi/L. However, a rigorous process for selecting successful, optimized systems has not yet been developed for widespread use by technicians and contractors.

Three new, and largely unvalidated, techniques are presented that may assist in determining the contributions to indoor radon levels from the domestic water supply and building materials and the approximate distribution of air infiltration leakage area in a structure. This document reports progress in research still underway. Additional data and observations are being made that may support, augment, or in some cases invalidate, some of the conclusions discussed here.

Other diagnostic techniques and tools under investigation in this and other studies include: use of tracer gases to quantify entrainment of building air into subsurface ventilation systems; creating flow and pressure maps for hollow block foundation walls; attempting to quantify and apportion subsurface ventilation from below slabs and from within block walls; estimating outside air ventilation that enters along the soil/house line; and development of a radon "sniffer" with faster recovery time between samples taken from test holes, entry points, and indoor air. Another new method will attempt to challenge an installed mitigation system by using a depressurization fan to gradually increase substructure depressurization and thereby determine the system failure point.

This work is cofunded by the U.S. Department of Energy (DOE) and by the U.S. Environmental Protection Agency (EPA). DOE support was from the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems Division, and from the Director, Office of Energy Research, Office of Health and Environmental Research, Pollutant Characterization and Safety Research Division under Contract No. DE-AC03-76SF00098. EPA support, under Interagency Agreement No. DW89931876-01-0 with DOE, was through the Office of Environmental Engineering Technology Demonstration, Office of Research and Development.

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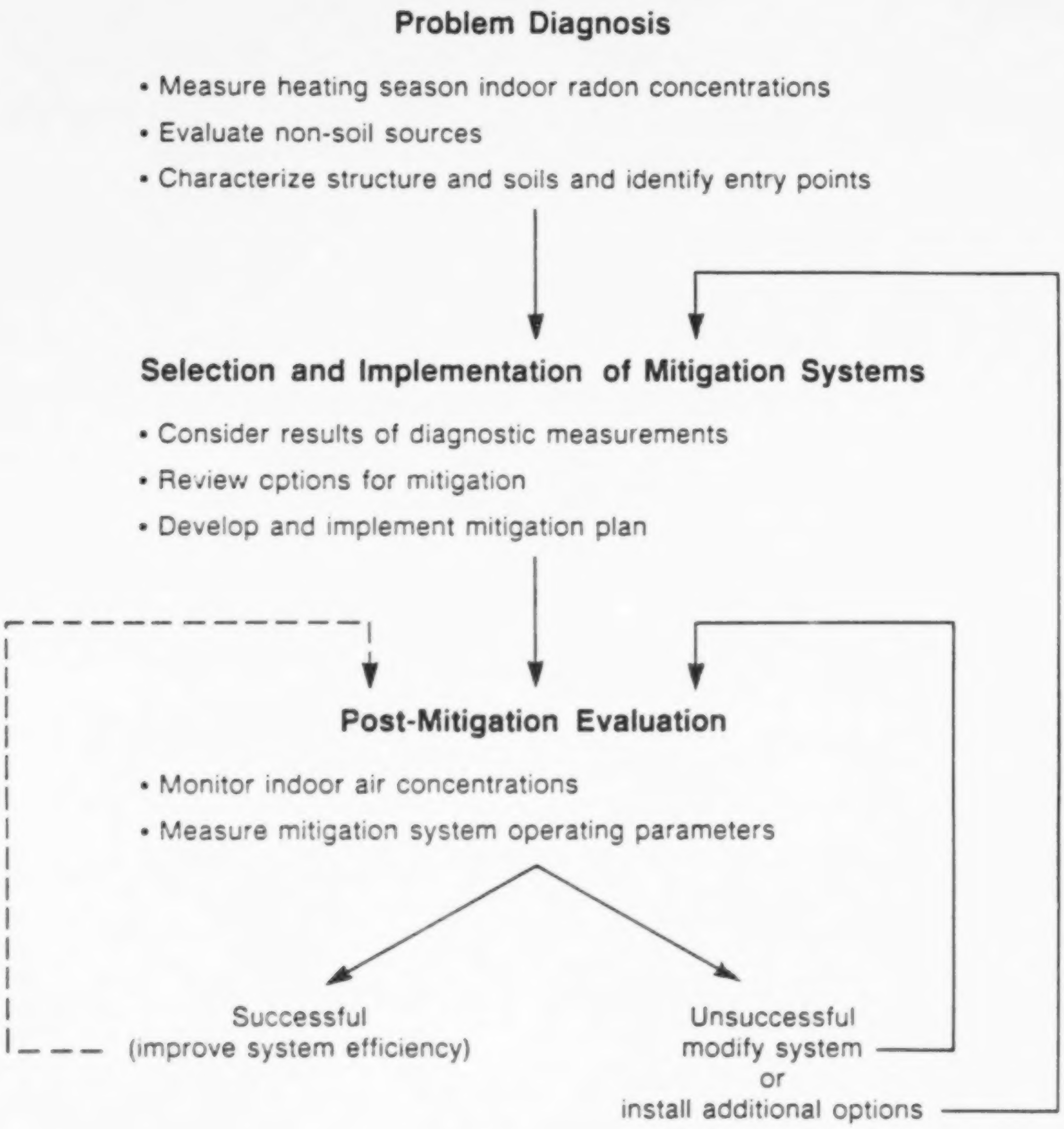
Figure 1

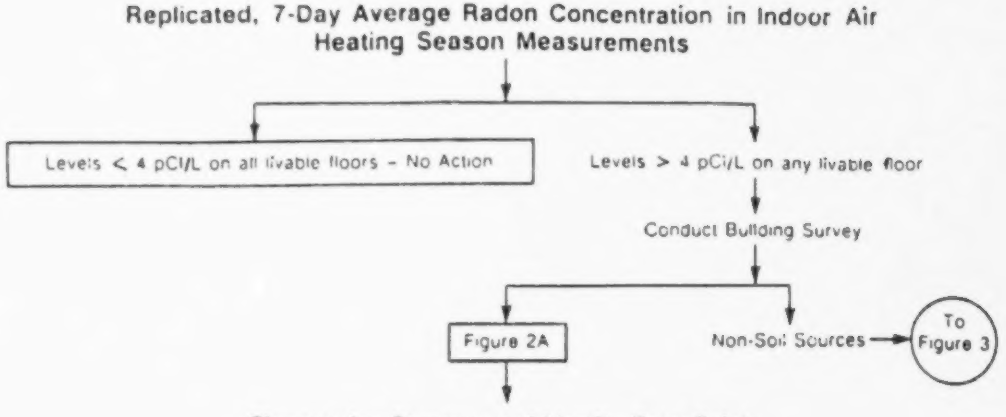
General Plan for Radon Control


Problem Diagnosis
• Measure heating season indoor radon concentrations
• Evaluate non-soil sources
• Characterize structure and soils and identify entry points
Selection and Implementation of Mitigation Systems
• Consider results of diagnostic measurements
• Review options for mitigation
• Develop and implement mitigation plan
Post-Mitigation Evaluation
• Monitor indoor air concentrations
• Measure mitigation system operating parameters
Successful
(improve system efficiency)
Unsuccessful
modify system
or
install additional options

XBL 871-8920

Figure 2

Problem Diagnosis


Replicated, 7-Day Average Radon Concentration in Indoor Air
Heating Season Measurements
Levels < 4 pCi/L on all livable floors – No Action
Levels > 4 pCi/L on any livable floor
Conduct Building Survey
Figure 2A
Non-Soil Sources
To Figure 3

Characterize Structure and Identify Entry Points

1.) **Conduct Visual Inspection:**

- Complete forms (site and floor plans, elevations, housing surveys, occupant questionnaire)
- Probe likely entry points (wall or floor cracks and holes, masonry interface, block wall top and holes) using stiff wire, screwdriver, and smoke tubes

2.) **Grab Sample Indoor Air under Natural Conditions**

Collect alpha scintillation cell grab samples under existing natural conditions from each unique building zone (garage, 2nd floor, 1st floor, basement, crawlspace, slab-on-grade areas).

3.) **Grab Sample Indoor Air under Mechanical Depressurization**

Collect grab samples using alpha scintillation cells from likely entry points and various building zones (this sampling could be repeated 2-3 days after the first sampling to document the variability in the technique due to environmental factors or sampling procedure)

Depressurize house using blower door to -10 Pa in substructure for > 30 min. (may not cause representative distribution of Rn throughout house)

a) grab sample of indoor air from each separately defined room or zone at mid-height

b) grab sample from cavities in bottom course of blocks approx. every 3 m (10 ft.) (through existing or 0.6 cm (1/4 in.) drilled inspection holes – fill holes on completion)

grab sample from 2 to 4 holes through slab (through existing or 1 cm (3/8 in.) drilled inspection holes)

c) grab sample from behind furred walls every 3 m (10 ft.) (Approx. 15 cm (6 in.) above floor)

d) grab sample from each obvious penetration to soil (condensate drains, floor drains, sumps, service penetrations, toilet and shower bases)

e) grab sample from wall/floor joints from each wall (where accessible)

f) grab sample from representative wall and floor cracks and French drain cavities

For e) and f), either:

1) Tape over joint, crack or French drain for approximately 60 cm (2 ft.) to either side of sample location and seal ends in French drain, or

2) Tape or seal with sealant, plastic film over joint/crack, evacuate from beneath film, and allow film space to charge with soil gas before collecting sample.

h) grab sample from other confined space in contact with the walls or floor, such as framed wall cavities

Count the activity for each sample (see text) and identify on house floor plan. Samples with concentrations ≤ room concentration are not likely entry points, those with concentrations ~ 2-3 X room concentration are possible entry points, and those with concentrations > 3 X room concentration are likely entry points.

4.) Qualify Air Movement From Likely Entry Points:

Depressurize house to ~30 Pa in substructure to characterize air movement from soil to house through entry points using Chemical smoke

Check flow at:
- substructure cracks, holes or joints in slabs or walls
- tops of block walls
- previously drilled test holes
- between floors
- exterior soil line
- other potential entry points: sumps, drains, shower and toilet bases, service entrances and penetrations

5.) Conduct Blower Door Tests to:

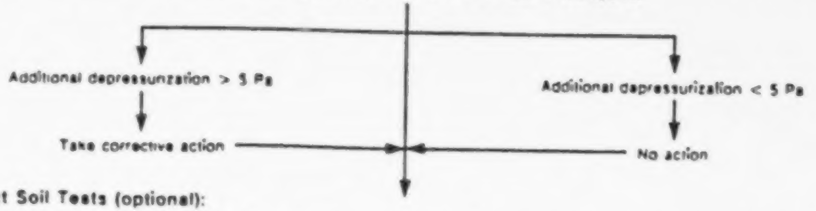
- measure the equivalent leakage area of:
  - the whole house
  - substructure only
  - superstructure only
- identify large holes and bypasses between upper floors and basements that will enhance the stack effect

6.) *Observe Ventilation Communication Within Block Walls and Beneath Slabs:*

- using high vacuum (2 m; 80 in. water) and high flow (170 m^{3}h^{-1}; 100 cfm) blower, depressurize subslab region and measure pressure drops and determine air movement at likely entry points and drilled test holes, including those in walls
- attach blower to block walls and check for air leaks in the walls and the extent of the induced ventilation at cracks and holes and drilled test holes.

7.) Observe Effect of Appliance Operation:

- using micromanometer determine additional depressurization of substructure due to appliance operation (dryer, furnace imbalance, fireplace, wood stove, exhaust fan) by cycling appliance on/off for approx. 20 cycles.


Additional depressurization > 5 Pa
Additional depressurization < 5 Pa
Take corrective action
No action

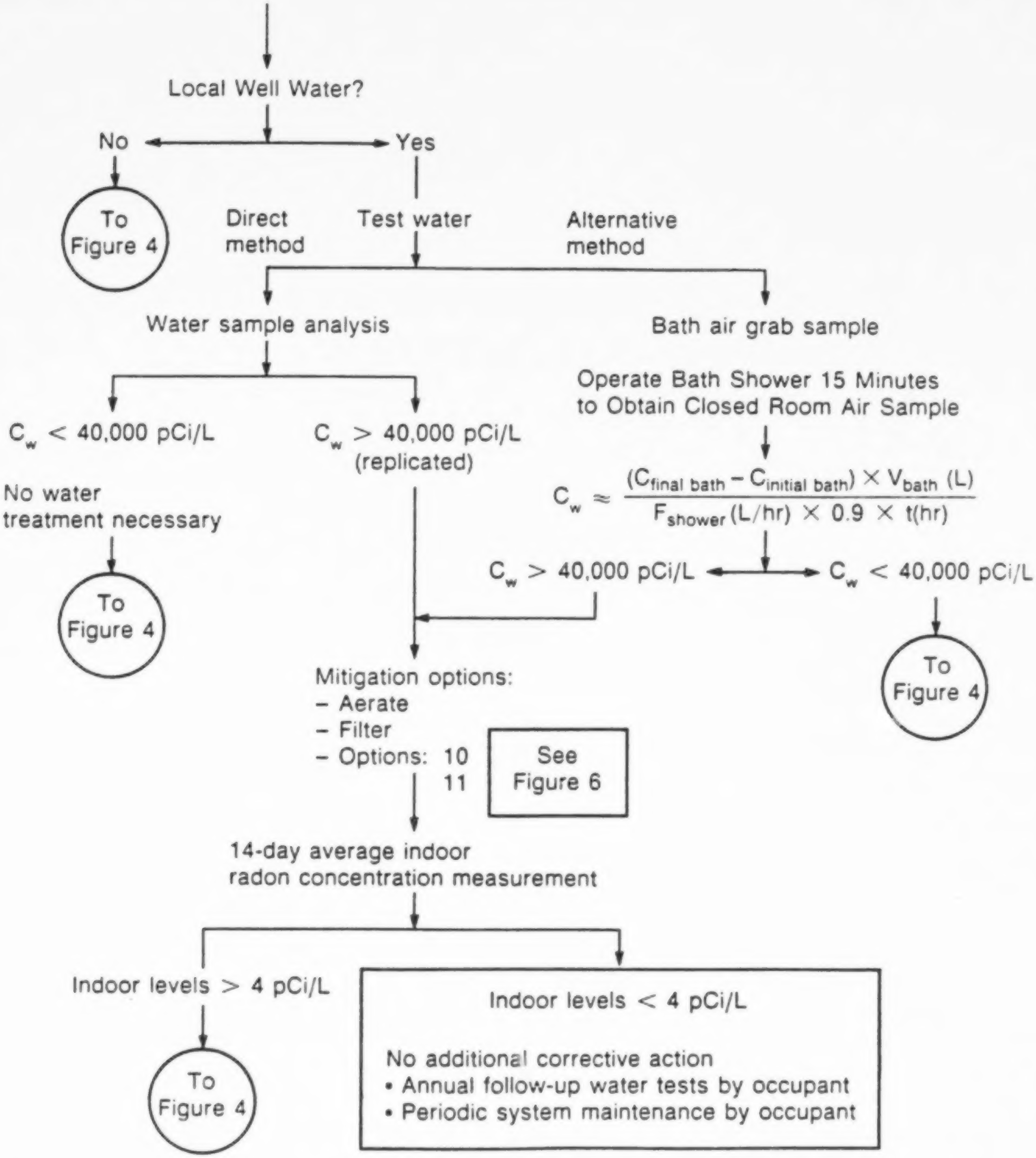
8) Conduct Soil Tests (optional):

- if Subsurface or weeping tile ventilation may be considered as mitigation options, conduct near-house soil air permeability test, and soil Ra test

XBL 871 8919

Figure 3

Radon in Water

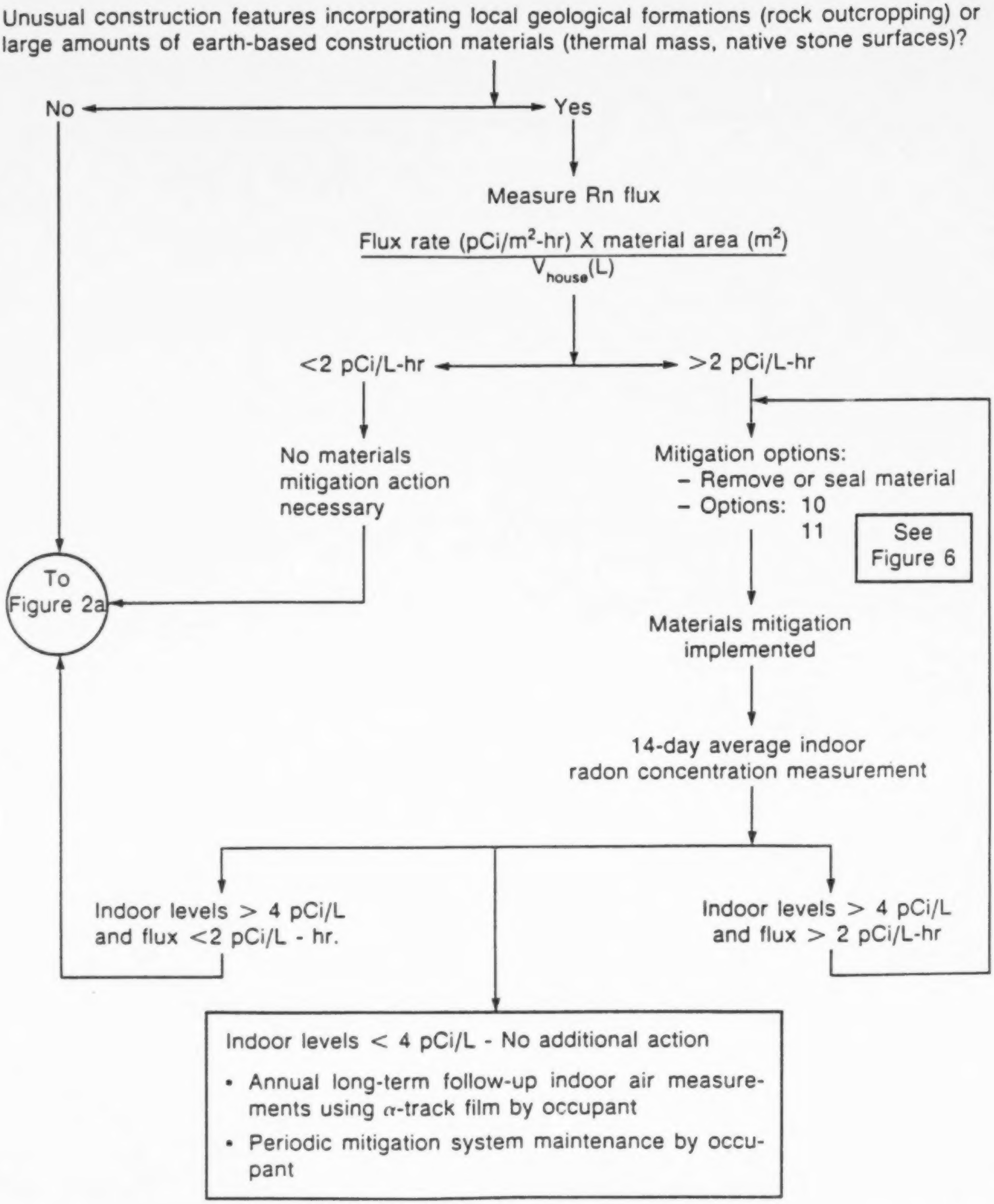


Local Well Water?
No
Yes
To Figure 4
Direct method
Test water
Alternative method
Water sample analysis
Bath air grab sample
Operate Bath Shower 15 Minutes to Obtain Closed Room Air Sample
$C_w < 40{,}000$ pCi/L
$C_w > 40{,}000$ pCi/L (replicated)
$C_w \approx \frac{(C_{\text{final bath}} - C_{\text{initial bath}}) \times V_{\text{bath}}\,(\text{L})}{F_{\text{shower}}\,(\text{L/hr}) \times 0.9 \times t(\text{hr})}$
No water treatment necessary
To Figure 4
$C_w > 40{,}000$ pCi/L
$C_w < 40{,}000$ pCi/L
To Figure 4
Mitigation options:
– Aerate
– Filter
– Options: 10
11
See Figure 6
14-day average indoor radon concentration measurement
Indoor levels > 4 pCi/L
To Figure 4
Indoor levels < 4 pCi/L
No additional corrective action
• Annual follow-up water tests by occupant
• Periodic system maintenance by occupant

XBL 871-8917

Figure 4

Radon Flux from Building Materials

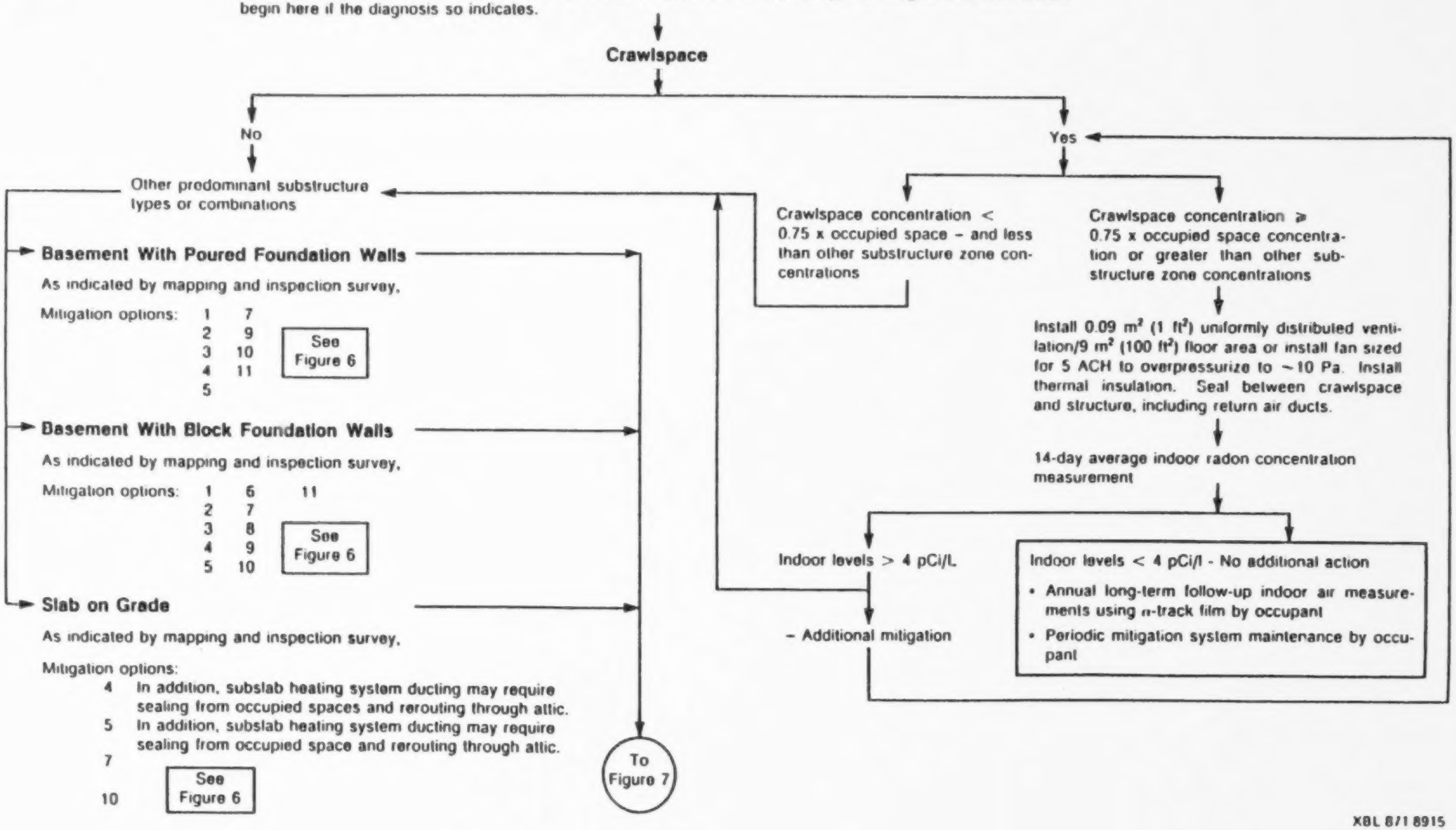

Unusual construction features incorporating local geological formations (rock outcropping) or large amounts of earth-based construction materials (thermal mass, native stone surfaces)?
No
Yes
Measure Rn flux
$\frac{\text{Flux rate (pCi/m}^2\text{-hr) X material area (m}^2\text{)}}{V_{house}\text{(L)}}$
<2 pCi/L-hr
>2 pCi/L-hr
No materials mitigation action necessary
Mitigation options:
– Remove or seal material
– Options: 10
11
See Figure 6
To Figure 2a
Materials mitigation implemented
14-day average indoor radon concentration measurement
Indoor levels > 4 pCi/L and flux <2 pCi/L - hr.
Indoor levels > 4 pCi/L and flux > 2 pCi/L-hr
Indoor levels < 4 pCi/L - No additional action
• Annual long-term follow-up indoor air measurements using α-track film by occupant
• Periodic mitigation system maintenance by occupant

XBL 871-8918

Figure 5

Selection of Mitigation Systems

After a careful review of the substructure(s), itemization of potential entry points, grab sample and air flow mapping, and occupant comments on operation of certain appliances, a mitigation plan should be developed. It should address control of radon for each house starting with one substructure type before moving to the next substructure type. Crawlspaces (if they exist) are typically the simplest type to mitigate and work should begin here if the diagnosis so indicates.


Crawlspace
No
Yes
Other predominant substructure types or combinations
Basement With Poured Foundation Walls
As indicated by mapping and inspection survey,
Mitigation options: 1 2 3 4 5 7 9 10 11
See Figure 6
Basement With Block Foundation Walls
As indicated by mapping and inspection survey,
Mitigation options: 1 2 3 4 5 6 7 8 9 10 11
See Figure 6
Slab on Grade
As indicated by mapping and inspection survey,
Mitigation options:
4 In addition, subslab heating system ducting may require sealing from occupied spaces and rerouting through attic.
5 In addition, subslab heating system ducting may require sealing from occupied space and rerouting through attic.
7
10
See Figure 6
To Figure 7
Crawlspace concentration < 0.75 x occupied space – and less than other substructure zone concentrations
Crawlspace concentration ≥ 0.75 x occupied space concentration or greater than other substructure zone concentrations
Install 0.09 m² (1 ft²) uniformly distributed ventilation/9 m² (100 ft²) floor area or install fan sized for 5 ACH to overpressurize to ~10 Pa. Install thermal insulation. Seal between crawlspace and structure, including return air ducts.
14-day average indoor radon concentration measurement
Indoor levels > 4 pCi/L
– Additional mitigation
Indoor levels < 4 pCi/l - No additional action
• Annual long-term follow-up indoor air measurements using α-track film by occupant
• Periodic mitigation system maintenance by occupant

XBL 871 8915

Figure 6

Mitigation Options

1) Sump sealing – active and inactive sumps
2) Floor drain sealing – if not water-trapped
3) a) Sump sealing and ventilation – active or inactive sumps with or without drain tile
   b) French drain sealing and ventilation
4) Subsurface ventilation

   A) Exterior
   - If homeowner prefers exterior
   - No landscaping interference
   - No utilities interference
   - Perimeter wall entry points

   B) Interior

   Gravel under floor slab
   - Central ventilation point every 45 m^2 (500 ft^2)

   No gravel
   - Locate near entry points

   Exhaust ventilation – soil impermeable, soil Ra high
   Supply ventilation – soil permeable, soil Ra low

   Drill series of small inspection holes in floor (1 cm; 3/8 in. diam.) and walls (0.6 cm; 1/4 in. diam.) to determine extent of pressure field.

5) Weeping tile ventilation
   - Where tile is accessible
   - Where tile is proximate to entry points
6) Wall ventilation – only if sealing successfully limits fan size to < 500 m^3h^{-1} (300 cfm) (smoke tubes at inspection holes to verify extent of ventilation)
7) Floor crack sealing
   - Where majority of cracks accessible
   - Where cracks localized – no network of cracks
   - Floating slab gap if no indication of water entry
8) Wall cracks and hole sealing
   - Where majority of openings are accessible
   - Where openings are localized
   - Only if blocks are open cell
9) Basement overpressurization (special option)
   - Where leakage of basement membrane is small
   - Where sealing of exterior and interior membranes is possible
   - Where if heating system is forced air, ductwork is tight and no forced air furnace registers present in basement
   - Where 1st floor vented combustion devices are not present

   Use blower door on basement to estimate approximate fan size: should be < 1 ACH delivery to achieve 5 Pa over-pressure
10) Balanced ventilation with heat recovery (special option)

    Multiple substructures:
    - If indoor concentrations > 4 pCi/L, < 20 pCi/L on all floors:
      - Ventilate all floors with 5 X original ventilation to < 2 ACH (new total)

    Basement only:
    - If basement concentrations < 80 pCi/L
      - Ventilate only basement where original basement ventilation < 0.2 ACH to new total < 3.5 ACH
    - System must be installed to match existing finish
11) Balanced ventilation w/out heat recovery (special option)
    - Unoccupied basements sealed and thermally insulated from occupied space.
    - In basement install 0.09 m^2 (1 ft^2) uniformly distributed vents to the outside per 4.6 m^2 (50 ft^2) floor area or install fan sized to 5 ACH to overpressurize substructure to 10 Pa

Options not considered here :
Coatings
Soil removal
Air cleaning

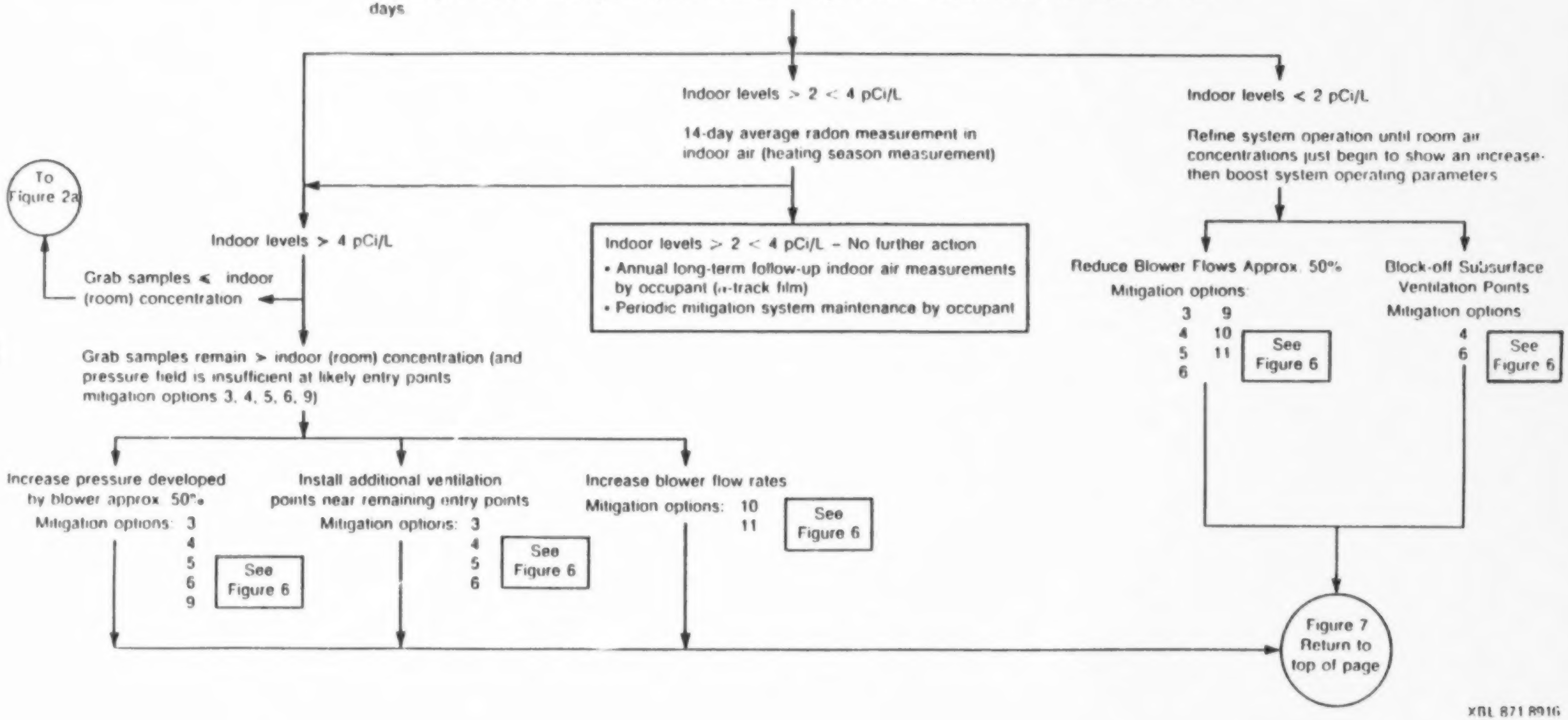
Figure 7

Post-Mitigation Evaluation

Measure: Temperatures and differential pressures in installed ducts, pipes; soil and building interior air flows developed by fans in ducts and pipes; radon concentrations in exhaust air streams.

Observe: Integrity of sealants, fillers, and bonding agents. Noise and vibration of fans and blowers. Inspect for leaks and bypasses in all systems. Correct if necessary.

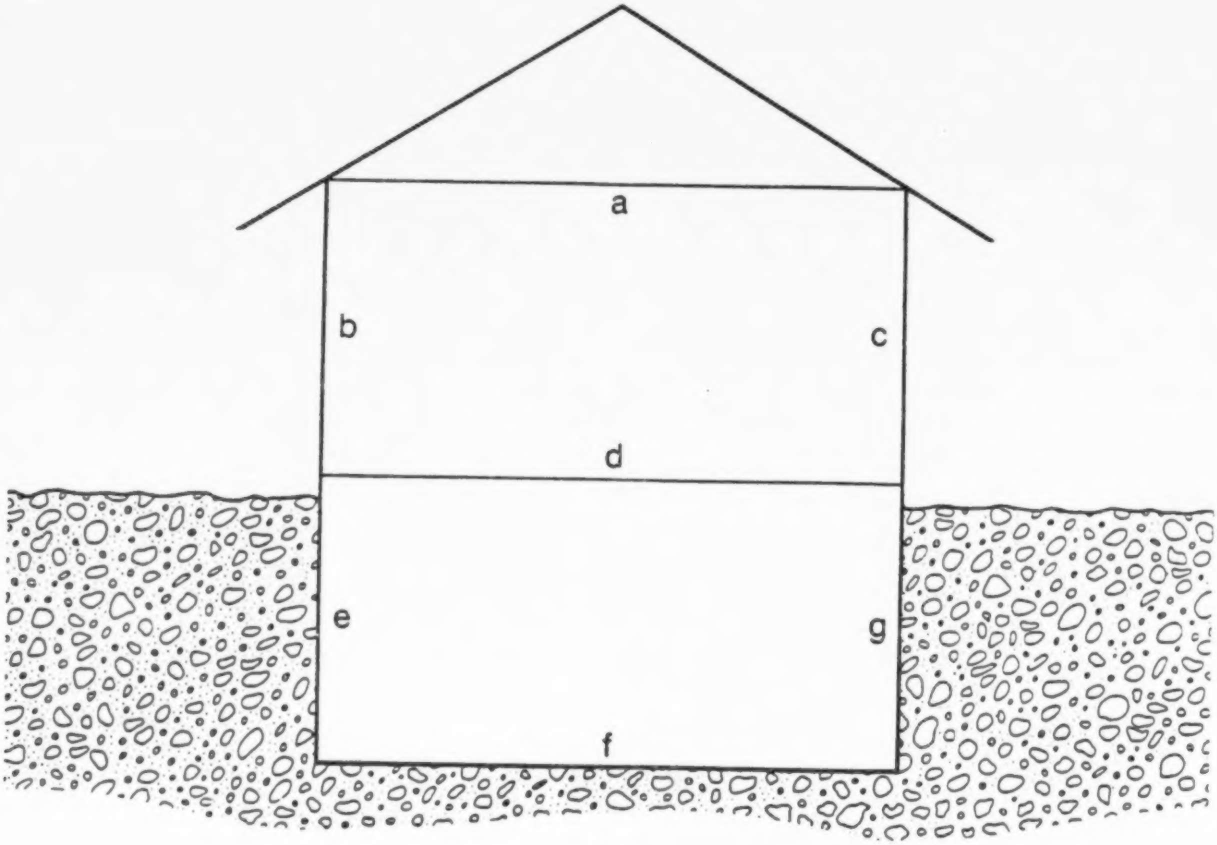
Repeat grab sample mapping survey and measure average indoor air concentrations for minimum of two days.


Indoor levels > 2 < 4 pCi/L
14-day average radon measurement in indoor air (heating season measurement)
Indoor levels < 2 pCi/L
Refine system operation until room air concentrations just begin to show an increase-then boost system operating parameters
To Figure 2a
Indoor levels > 4 pCi/L
Grab samples < indoor (room) concentration
Indoor levels > 2 < 4 pCi/L – No further action
• Annual long-term follow-up indoor air measurements by occupant (α-track film)
• Periodic mitigation system maintenance by occupant
Reduce Blower Flows Approx. 50%
Mitigation options:
3 9
4 10
5 11
6
See Figure 6
Block-off Subsurface Ventilation Points
Mitigation options
4
6
See Figure 6
Grab samples remain > indoor (room) concentration (and pressure field is insufficient at likely entry points mitigation options 3, 4, 5, 6, 9)
Increase pressure developed by blower approx. 50%
Mitigation options: 3 4 5 6 9
See Figure 6
Install additional ventilation points near remaining entry points
Mitigation options: 3 4 5 6
See Figure 6
Increase blower flow rates
Mitigation options: 10 11
See Figure 6
Figure 7 Return to top of page

XBL 871 8916

Figure 8

Distribution of Structure Effective Leakage Areas



Whole building $(ELA_w) = a + b + c + e + f + g$

Superstructure $(ELA_p) = a + b + c + d$

Substructure $(ELA_b) = d + e + f + g$

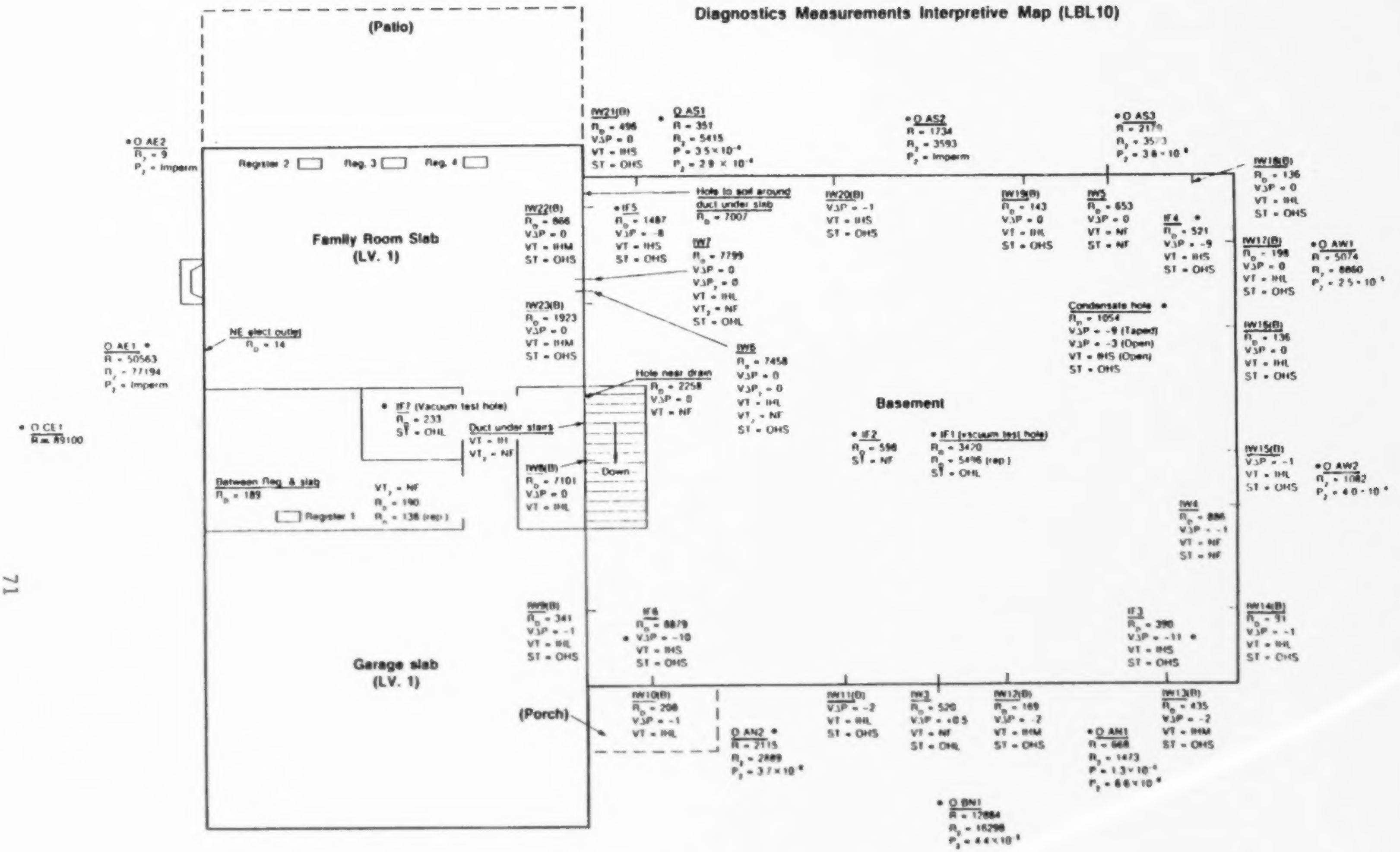
Substructure ceiling $(ELA_c) = d$

Substructure walls/floor $(ELA_f) = e + f + g$

XBL 871 8921

Figure 9

Diagnostics Measurements Interpretive Map (LBL10)


(Patio)
• O AE2
R_2 = 9
P_2 = Imperm
Register 2
Reg. 3
Reg. 4
Family Room Slab
(LV. 1)
IW22(B)
R_D = 868
VΔP = 0
VT = IHM
ST = OHS
IW23(B)
R_D = 1923
VΔP = 0
VT = IHM
ST = OHS
NE elect outlet
R_D = 14
O AE1 •
R = 50563
R_2 = 77194
P_2 = Imperm
• O CE1
R = 89100
• IF7 (Vacuum test hole)
R_D = 233
ST = OHL
Duct under stairs
VT = IH
VT_2 = NF
IW8(B)
R_D = 7101
VΔP = 0
VT = IHL
Between Reg. & slab
R_D = 189
Register 1
VT_2 = NF
R_D = 190
R_D = 138 (rep.)
Down
Garage slab
(LV. 1)
IW9(B)
R_D = 341
VΔP = -1
VT = IHL
ST = OHS
(Porch)
IW10(B)
R_D = 208
VΔP = -1
VT = IHL
IW21(B)
R_D = 496
VΔP = 0
VT = IHS
ST = OHS
• O AS1
R = 351
R_2 = 5415
P = 3.5 × 10^{-8}
P_2 = 2.9 × 10^{-8}
Hole to soil around duct under slab
R_D = 7007
• IF5
R_D = 1487
VΔP = -8
VT = IHS
ST = OHS
IW7
R_D = 7799
VΔP = 0
$VΔP_2$ = 0
VT = IHL
VT_2 = NF
ST = OHL
IW6
R_D = 7458
VΔP = 0
$VΔP_2$ = 0
VT = IHL
VT_2 = NF
ST = OHS
Hole near drain
R_D = 2258
VΔP = 0
VT = NF
• O AS2
R = 1734
R_2 = 3593
P_2 = Imperm
IW20(B)
VΔP = -1
VT = IHS
ST = OHS
Basement
• IF2
R_D = 598
ST = NF
• IF1 (vacuum test hole)
R_D = 3420
R_D = 5496 (rep.)
ST = OHL
IW19(B)
R_D = 143
VΔP = 0
VT = IHL
ST = OHS
IW5
R_D = 653
VΔP = 0
VT = NF
ST = NF
• O AS3
R = 2179
R_2 = 3573
P_2 = 3.8 × 10^{-9}
IF4 •
R_D = 521
VΔP = -9
VT = IHS
ST = OHS
IW18(B)
R_D = 136
VΔP = 0
VT = IHL
ST = OHS
IW17(B)
R_D = 198
VΔP = 0
VT = IHL
ST = OHS
• O AW1
R = 5074
R_2 = 8860
P_2 = 2.5 × 10^{-9}
Condensate hole •
R_D = 1054
VΔP = -9 (Taped)
VΔP = -3 (Open)
VT = IHS (Open)
ST = OHS
IW16(B)
R_D = 136
VΔP = 0
VT = IHL
ST = OHS
IW15(B)
VΔP = -1
VT = IHL
ST = OHS
• O AW2
R_2 = 1082
P_2 = 4.0 × 10^{-9}
IW4
R_D = 886
VΔP = -1
VT = NF
ST = NF
IF6
R_D = 8879
• VΔP = -10
VT = IHS
ST = OHS
IF3
R_D = 390
VΔP = -11 •
VT = IHS
ST = OHS
IW14(B)
R_D = 91
VΔP = -1
VT = IHL
ST = OHS
O AN2 •
R = 2115
R_2 = 2889
P_2 = 3.7 × 10^{-9}
IW11(B)
VΔP = -2
VT = IHL
ST = OHS
IW3
R_D = 520
VΔP = +0.5
VT = NF
ST = OHL
IW12(B)
R_D = 169
VΔP = -2
VT = IHM
ST = OHS
• O AN1
R = 668
R_2 = 1473
P = 1.3 × 10^{-8}
P_2 = 6.6 × 10^{-9}
IW13(B)
R_D = 435
VΔP = -2
VT = IHM
ST = OHS
• O BN1
R = 12884
R_2 = 16298
P_2 = 4.4 × 10^{-9}

Ambient air samples

10/29/86	Upstairs hall	= 11 pCi/L
	Bathroom (after 10 min. shower)	= 12 pCi/L
	Level 1 din. rm.	= 22 pCi/L
	Level 1 fam. rm.	= 8 pCi/L
	Basement	= 124 pCi/L
10/30/86	Level 1 din. rm.	= 54 pCi/L
	Basement	= 141 pCi/L

Flux measurements

Wall	Basement wall	= 52.78 pCi/m²·s
Floor	Basement floor	= 0.325 pCi/m²·s
	Fam. rm. floor	= 0.371 pCi/m²·s

Water concentration = 218 pCi/L

Key to Symbols

Measurements

VΔP = Vacuum test ΔP (Pa) – hole IF1, basement reference
$VΔP_2$ = Vacuum test ΔP (Pa) – hole IF7, LV 1 reference
VT = Vacuum test flow, smoke movement, hole IF1
VT_2 = Vacuum test flow, smoke movement, hole IF7
ST = Zone depressurized to – 30 Pa, smoke movement
Flow direction – IH = Into hole/crack
OH = Out of hole/crack
NF = No flow
Approx. flow velocity – S = Strong
M = Moderate
L = Slight
P = Permeability (cm²)
R = Approx. radon concentration (pCi/L)
Subscript – D = Diagnostics
2 = September
Blank = October

Locations

I = Indoor
W = Wall
(B) = Into block wall cavities
Blank = Through wall into soil
F = Through floor
O = Outdoor
A = ~ 0.5 m from house
B = ~ 1.5 m from house
C = ~ 3.0 m from house
N,E,W,S = Orientation to compass direction
1,2,3,... = Arbitrary sample location number

XBL 871-8914

GUARANTEED RADON REMEDIATION THROUGH SIMPLIFIED DIAGNOSTICS

David Saum and Marc Messing
INFILTEC Radon Control services
P.O. Box 1533
Falls Church, VA 22041

1.0 INTRODUCTION

How can guaranteed radon remediation performance be provided at a price that homeowners are willing to pay? The paper summarizes the diagnostic procedures developed by INFILTEC to achieve this goal. Assumptions will be pointed out, as well as problems and questions. INFILTEC is submitting a patent on the pressure/flow test equipment and techniques described in this paper.

2.0 TIME/COST

The customer seems to be willing to pay for diagnostics if it will result in a better system installation with a higher level of confidence in the remediation. Two to three hours of diagnostics may be an upper limit on time, with a corresponding cost of $200 to $300.

3.0 RADON SOURCE MAPPING

The radon source is assumed to be primarily under the slab and at levels 10 to 1000 times the levels in the air. Walls, whether block or concrete are assumed to not be a problem unless the source mapping does not show any significant levels. Source mapping consists of drilling approximately 5 small holes (one at each corner and one in the center) and counting a Lucas cell for 5 one minute intervals while pumping subslab air through the cell. The cell is allowed to clear for two or three minutes between holes. If wide deviations in levels are noted, or the slab is complex in shape, or the slab is large, then more holes may be drilled and tested. Although the radon counts do not allow for daughter equilibrium, the relative levels around the slab are of most interest and the actual levels are assumed to be 1.5 to 2 times as high as the count indicates. The combined time for drilling the holes and counting is approximately one hour. When the source mapping is completed, the slab areas of most interest (highest radon) should be known. Drains, sumps, and crawl spaces are also tested similarly. Walls are only tested if the subslab levels seem too low to account for the previous screening and confirmation measurements by the homeowner.

4.0 PRIMARY REMEDIATION TECHNIQUE

Sub-slab suction is assumed to be the primary radon source remediation technique which should be attemped if at all possible. Radon is assumed to be prevented from entering the house if there is an adequate pressure barrier at the slab. Wall suction has not been found to be necessary in any houses. Some houses have been encountered that have not been remediated yet, due to complex construction that makes sub-slab suction difficult.

The work described in this paper was not funded by the U.S. Environmental Protection Agency. The contents do not necessarily reflect the views of the Agency and no official endorsement should be inferred.

5.0 SUB-SLAB PRESSURE/FLOW MAPPING

A portable suction system with flow and pressure gauges (blower floor) is installed in a 1" diameter drilled hole or a sump hole that is near to the radon concentrations and is also near a good venting location. Selection of a good suction point involves many cosmetic, venting, radon source, and customer considerations. The fan for the suction system is outside to avoid worker exposure to high radon concentrations, and a long flexible tube is used to connect the fan to the suction hole. Note that apha-track measurements taken during months of almost daily diagnostic and remedial work, show radon exposures below 4 pCi/l. Two types of measurements are made: flow versus pressure in the hole, and pressure in the suction hole versus pressure in the test holes around the slab. If there is no pressure induced in the test holes by the suction hole pressure, other suction holes may be drilled on the assumption that the suction hole was in a dead spot. If the suction hole pressure induces large pressures at the perimeter test holes, then the flow has been shown to be good, and tight enough to induce pressure with standard fans. Cases of marginal pressure and flow require further analysis.

6.0 EDGE PRESSURE RULE OF THUMB

Simple rules of thumb are assumed to determine the minimum adequate pressure across the slab. Houses are assumed to be so leaky that stack pressure is the dominant cause of suction on the slab. The neutral pressure point is assumed to be in the attic, and the stack maximum stack pressure on the slab is assumed to be approximately 0.001" WC per foot of building height. This leads to an approximate rule of thumb of 0.015" WC of suction for the design pressure in a typical house. This is the worst case pressure to be exerted across the slab. Actual measurement of stack and appliance induced pressure are complicated and do not seem to be necessary in most cases.

7.0 ESTIMATING SYSTEM PERFORMANCE

When marginal flow and pressure measurments are encountered, the capability of a particular fan/pipe system to achieve adequate edge pressure can be calculated from measured pressure and flow data. Section 11 of this paper gives a sample of this type of calculation. It allows tradeoffs to be made between fan sizes, pipe, venting, etc.

8.0 QUALITY CONTROL

The installed sub-slab system must be carefully checked to determine if it actually achieves the required pressure field across the slab and whether is has leaks that could cause radon inflow back into the house. A separate quality control visit is made after the system has been operating for a least 24 hours. A pressure gauge is permanently installed on all remediation systems to allow contractor and the homeowner to quickly verify proper fan operation. Freon is injected into the system while the fan is on and a freon leak detector is used to detect leaks in the fan, pipe and vent location. Radon grab samples are taken to measure remediation performance and the homeowner is given charcoal and alpha-track test kits.

9.0 INFILTEC RADON REMEDIATION PERFORMANCE

LOCATION	TYPE OF HOUSE	BEFORE REMEDIATION	AFTER REMEDIATION
Mt. Airy	Split Level	100 pCi/l	3.3 pCi/l
Herndon	Colonial	30	3.1
Owings Mills	Ranch	26	1.6
Potomac	Split Level	215	1.6
Potomac	Colonial	7	2.0
Damascus	Ranch	11	1.4
Damascus	Ranch	45	2.0
Mt. Airy	Colonial	22	1.3
W. Bethesda	Modern	67	4.5*
Columbia	Colonial	62	3.1
Potomac	Modern	20	0.5
Columbia	Colonial	59	1.3
Columbia	Colonial	16	1.6
Columbia	Ranch	11	1.3
Reston	Townhouse	150	1.6
Germantown	Colonial	40	0.6
Laytonsville	Ranch	160	1.2
Herndon	Colonial	12	0.8
Bethesda	Ranch	17	2.0
Damascus	Ranch	18	1.4
Silver Spring	Ranch	12	0.2
Owings Mills	Modern	44	1.8

The readings before remediation may be summer or winter charcoal tests in the basement, but the readings after remediation are all winter charcoal tests in the basement.

* reading after 1st stage remediation on house with slab on rock.

10.0 EQUIPMENT REQUIRED FOR DIAGNOSTICS

Very few remediation contractors are now willing to buy the full range of equipment that these diagnostics require.

- Continuous Radon Monitor ($3500-$4500)
- Rotary Hammer and other tools ($300-$600)
- Pressure Gauge (Analog model $60, Digital model $600-$1400)
- Blower Floor (Analog model: $2500?, Digital model: $5000?)
- Freon Leak Detector and Freon ($150-$250)

TOTAL COST RANGE: $6500 to $12000

11.0 SAMPLE SUBSLAB PERFORMANCE CALCULATION

The objective of this calculation is to predict the pressure that will be induced under the slab by specific fan and pipe configuration. The calculation requires formulas for the pressure/flow characteristics of the fan, pipe configuration, and the subslab. The fan and pipe formulas are available but the subslab characteristics must be measured.

11.1 SUCTION HOLE PRESSURE

Flow/Pressure Measurements By INFILTEC Blower Floor:

PRESSURE (" WC)	FLOW PRESSURE (" WC)	COMPUTED FLOW (CFM)
0.136	0.150	83.27
0.120	0.134	78.70
0.100	0.110	71.31
0.090	0.095	66.27
0.080	0.082	61.57
0.060	0.058	51.78

These data then can be fit to a power law flow equation with the following results:

- * Correlation Coefficient = 0.998
- * Flow Exponent (N) = 0.581
- * Flow at 1 " WC = 268.6 CFM
- * Effective Leakage Area (ELA) = 12 square inches

Note that this basement is 25' by 40' with a perimeter of 130'. If we assume that all of the leakage is due to the perimeter crack, then this crack has a predicted width of about 0.008".

Now that we have a formula relating subslab pressure and flow, we can write an equation equating the pressure generated by the fan to the pressure loss in the pipe and in the subslab:

Fan Pressure = Pipe Pressure Loss + Suction Hole Pressure Loss

This equation can be solved for flow, and this flow can be used to evaluate each pressure component. Suppose we assume the following fan and pipe characteristics:

11.2 FAN PRESSURE

Kanalflakt T-2 fan specifications can be written as the following equation:

$$Q = 270 - 116P$$

where Q is the flow through the fan in CFM
P is the pressure across the fan in " WC

11.3 PIPE SYSTEM PRESSURE

Consider a system with ten feet of 4" diameter PVC with one 90 degree, one vent cap, and one screen. An approximate equation for air flow through a smooth round pipe of length L and diameter D can be derived from handbook graphs:

$$Q = (.027LD\ \mathrm{EXP}(2.75))\ (P\ \mathrm{EXP}(.55))$$

where Q is the flow through the fan in CFM
D is the pipe diameter in inches
P is the pressure drop in one foot of pipe
L is the length of the pipe in feet

Assume an equivalent pipe length for resistance of pipe components:

one 90 degree Bend = 50 pipe diameters
one vent cap = 50 pipe diameters
one screen = 50 pipe diameters

Equivalent Total length = $150D/12 + 10 = 60$ feet

Solving for pressure:

Fan Pressure = $(270 - Q)/115$
Pipe Pressure Loss = $(Q/(.027LD\ \mathrm{EXP}\ (2.75))\ \mathrm{EXP}\ (1.818)$
Suction Hole Pressure = $(Q/C)\ \mathrm{EXP}(1/N)$

Substituting into the subslab system equation:

$$(270 - Q)/115 = (Q/(.027LD\ \mathrm{EXP}(2.75))\ \mathrm{EXP}\ (1.818) + (Q/C)\ \mathrm{EXP}(1/N)$$

This equation can be solved interatively for Q:

* Steady-state flow = 141 CFM

And the flow can be used to solve for the component pressures

* Fan Pressure = 1.11" WC
* Pipe Losses = 0.78" WC
* Suction Hole Pressure = 0.33" WC

This compares well with the measured 0.35 " WC subslab suction generated by the installed system.

The pressure at the suction hole can now be used to estimate the worst case pressure induced across the slab, far away from the suction hole (called the "edge pressure"). In this particular basement, the edge pressure was .020" WC when the pressure of 0.25 " WC was induced on the suction hole by the blower floor. In some cases, the realation between the suction hole pressure and the edge pressure is linear, but in others it is not and in those cases the edge pressure must be predicted by finding a curve fit between it and the suction hole pressure.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

FOLLOW-UP DIAGNOSTICS - HOW WELL DOES THE MITIGATION WORK AND DOES IT MEET THE GUIDELINES?

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Many of the diagnostic procedures covered by the other presentations in the Radon Diagnostics Workshop must be employed before a choice of mitigation method is made. We will not review each of these procedures but rather will touch briefly on items that have not been included in the other presentations.

Infrared scanning of interior surfaces

This diagnostic technique is used to uncover air leakage sites and air flow patterns within the building. Outside air is normally a different temperature, colder or hotter, than interior surfaces. When this outside air enters the building it alters the local surface temperatures and thus can be detected with an infrared scanning device which is sensitive to small changes in surface temperature. Air flowing upward in the home from a cooler or warmer basement environment again results in alteration of interior surface temperatures. If the blower door is used to increase the upward air flow (operating upstairs in the depressurization mode) the air path is made even more evident. Since this is likely to be a pathway for radon transport, the IR technique can prove useful in documenting such radon paths as well as evaluating how well separated the living space is from the basement/crawlspace. This degree of separation may directly affect the choice of mitigation method.

Tracer gas measurements.

Flowpaths, as just described, can also be evaluated using a tracer gas. The tracer gas is injected into the basement or other radon source locations, and the path that air takes is then determined from local measurements, over time, of the concentrations of the tracer gas. The tracer gas detection equipment may take a variety of forms from simple freon leak detectors to portable gas chromatograph electron capture-based devices. Cost may vary from $100 to more than $5,000 per detector.

Another application of tracer gases is for evaluation of the air infiltration/ventilation rate in the house or zone. One method is to add a tracer gas, allow it to mix with the air in the space (natural convection helps the mixing process, and running the furnace blower normally achieves the mixing in less than 10 minutes), and then monitor the decay in the tracer gas concentration levels. This "decay method" or "dilution method" (see ASTM Standard E779 for details) allows one to directly determine the air exchange rate, i.e., the faster the decay the higher the rate. Another method, such as "constant injection" of the tracer gas, may employ tracer emitters and passive samplers to evaluate the air infiltration rate. Several different tracer gases can be used with this method so that flow from zone-to-zone can be measured. If each zone is maintained at a constant tracer gas concentration, i.e., the "constant concentration method", flow rates are then directly proportional to the tracer gas flow rate to each zone. Systems are available to measure air infiltration rates in 10 zones simultaneously. Rather than porbable diagnostics equipment, this is computer-controlled ventilation monitoring equipment, priced in the $20,000 range.

All of the methods described above evaluate building tightness and flow paths and therefore may directly influence the choice of mitigation device.

During and after the mitigation device is in place.

The preceding discussion on diagnostic techniques is useful for choosing the correct mitigation approach. Now we wish to shift attention to what should take place during and after the mitigation device is in the house. Mitigation installation diagnostics are important to see whether or not the equipment is working correctly.

During installation of a mitigation system, such as subslab ventilation where one is exhausting radon-laden air, adding a tracer gas to that air allows one to evaluate where leaks in the system may be occuring, and whether or not exhausted air is being carried back into the house. Of course the radon itself serves as a tracer but the measurement equipment tends to be less portable and more expensive than using freon and a freon leak detector, for example.

Flow balance.

Many of the mitigation devices rely on withdrawing radon from critical areas such as under the basement slab. Such air movement is governed by the standard flow relationship, namely:

$$Q \propto A \sqrt{\text{delta P}}$$

where Q is the air flow rate, A is the area for the flow passage and delta P is the differential pressure. This means that if the air passage is non restrictive, i.e., A is large, then a small differential pressure may be all that the system can provide when the exhaust fan is flowing at its rated Q value. On the other hand, if A is very small, delta P will become very large and the rated Q may not be reached since the fan will stall, or run very inefficiently.

Since there is often more than one branch to the mitigation system piping, one wishes to make certain that all the critical radon source areas are being appropriately treated. For example, in a house with a subslab system treating a basement slab and crawlspace slab, one wishes to balance the system so that both slabs are being treated equally. In the case of high radon sources in one area, that particular area should receive the higher flow.

Diagnostic methods involve flow measurements in the various duct branches using heated wire anemometers, pitot tube and micromanometer, or other flow measurement systems that can be easily inserted into the piping. Provision for dampers in the piping lends itself to rapid flow adjustment of the branches. Measurement of the exhaust for radon concentration level can also help determine the best adjustment or balance of the system.

Energy and Radon Mitigation

Once the radon mitigation system is working satisfactorily from a radon reduction point-of-view, it is then worthwhile to consider other factors. Lowering the fan speed, providing the radon concentration in the home does not rise, offers an ability to save energy in two ways: first the fan electrical energy is reduced and second one limits the energy loss assocaited with the conditoned interior air that is exhausted with the radon laden air. From a diagnostics standpoint, energy savings from either a lower fan speed or smaller fan can be determined by the use of a wattmeter. The evaluation of how much additional air is being removed from the house must rely upon air exchange measurements using tracer gases. For example, placing a tracer gas in the basement and measuring the concentration there and then measuring the concentration in the exhaust from the subslab system allows an evaluation of how much of the air was basement air and thus to evaluate the energy penalty. It is evident from test home data that exhausting systems do alter the "normal" air infiltration rates and raise energy use. This often can be limited to a minor increase by appropriate mitigation system adjustments.

When mitigation systems are used which cause air to leave the basement, we must be sure that the air flow is not causing a pressure reduction that results in combustion products from the heating system to be drawn into the basement and home. Use of heated wire anemometer, pressure micromanometer, and smoke tracers can prove useful diagnostics tools for evaluating proper flow direction in the furnace exhaust. Remember that the greatest tendency for reverse flow will be under mild weather conditions.

Also, where the piping of the mitigation systems leaves the conditioned space, the opening must be completely sealed to avoid undesirable energy losses. Use of smoke sticks, tracer gas or IR scan will immediately revel such shortcomings. In the same area of "good installation" the system piping must have the appropriate slope so that condensing moisture will not form a local puddle and plug the exhaust flow. This is a very real problem with large volumes of water being condensed. Use of bubble levels and careful measurements and firm bracketing avoids these difficulties.

Conclusions

This has been a very brief review of some additional diagnostic procedures that should prove useful in the choice of the mitigation approach and whether the mitigation system is performing as desired. Diagnostic techniques are focused on providing quantitative and qualitative data to improve the chances for successful radon mitigation. At times the most critical procedure will prove to be something very house specific, meaning the investigator must continually ask critical questions and ponder those measurements that "don't make sense" while looking for the "right solutions."

PART C WORKSHOP DISCUSSIONS

The following are the actual discussions that took place in the Workshop as transcribed from audio tapes. Efforts have been made to identify the originators of question (Q), answers (A), or comments (C). This identification is by initials in the parenthesis before each quotation. Please refer to the list of attendees for this information.

As has been the rationale throughout this Workshop the discussions will be treated in four phases:

I. Radon Problem Assessment

II. Pre-Mitigation Diagnostics

III. Mitigation Installation Diagnostics

IV. Post-Mitigation Diagnostics

Phase I - WORKSHOP DISCUSSIONS - RADON PROBLEM ASSESSMENT

M. Mardis, Chairman

C(M.M.) "Phase I is the Initial Radon Problem Assessment and we want to focus our attention on diagnostic tools that will prove useful to identify radon source strength and location; to characterize the existing building structure; evaluate occupancy factors; and measure the radon concentration in the different zones within the structure.

The panel will begin the discussion, and we will start with mobile scans with Mike Koontz:

C(M.K.) "I would like to start out with a few background comments about a statewide survey in Florida. That is, I'll start with a regional perspective and lead into the specifics of a house."

"The purpose of the Florida study is to identify areas of the state which are problematic in terms of radon. There is an environmental rule there that basically states that if an area is declared to have problems then certain types of radon-resistant construction methods are to be used in new construction. In that study we're measuring radon indoors, short-term with charcoal canisters, and measuring soil gas concentration. We're also using portable scintillometers to measure radiation instantaneously inside and outside the houses."

We're guiding our survey as to high-concentration areas with USGS 1-24,000 scale maps representing 8 mile x 8 mile squares (quad) of land. We originally thought that as we had our field techs going from one place to another searching for houses and making these measurements it might be useful to use these portable scintillometer to make measurements while driving to give us a better feel for local variations. Unfortunately we found that the road surface was a confounding factor, and we couldn't make reliable measurements that way. This leads to my question with respect to measurements from mobile vans: what sort of false positives might you see due to road surface or other potential confounding factors?

"Alan spoke about mapping data from NURE or other sources. We've found that the 1:24,000 quad is a convenient mapping tool. We've looked at the NURE data, not only the radiation values, but another possibly valuable addition from the NURE data is that they do have so-called geologic map units associated with each reading. Again, bearing in mind that at least in Florida, flight lines are sometimes 18-20, miles apart, depending on whether you're looking N-S or E-W. Nonetheless, the 1:24,000 quad can be a convenient way of looking for subcountry variations at a gross level. The NURE data, both the brightness and the geological data, seem to be helpful, and we're seeing also that there are fairly good correlations between soil gas concentrations and indoor concentration, again, at this more aggregate level. I don't think it works at the neighborhood level, looking at house to house variations.

"These state-wide data can be used to identify potentially "hot" areas. Within a given area there may be variation of an order of magnitude."

Q(T.T.) "During your work in Florida, you did gamma surveys. We've heard here that some studies have shown that gamma and other emanation studies in some parts of the country (like Grand Junction, Colorado) are usefully correlated with indoor levels, but that in other areas (such as in the Reading Prong) the case is not so straightforward. What experience did you have in Florida?"

A(M.K.) "We haven't analyzed all the data yet, but we did see that the strongest correlation of indoor radon concentrations is our soil measurements made with alpha tracks. We do see some correlations, even indoors, between concentrations of uranium and radon, but we're not in a position yet to say how well it works."

Q( ) "How are the soil measurements made?"

A( ) "Without the traps they're in 12 to 15 inches."

Q( ) "What kind of correlations are you getting?"

A(M.K.) "The correlation coefficent between soil measurements and individual houses has been 0.5, whereas using the quad as a unit of analysis with the soil measurements, the correlation coefficent has been 0.7. We've taken measurements in, say, 4-6 houses per quad. 0.7 is the correlation between mean soil concentration and mean indoor concentration. Q(M.M.) "Do these houses have basements?"

A(M.K.) "This becomes an issue when one is doing mass screening using charcoal canisters indoors and looking for problem areas. Ideally one would be able to identify a "marker house" of a design found throughout the state so as to avoid the confounding effects of measuring in houses of completely different construction types. Fortunately, in Florida, perhaps 75% single-family homes are slab-on-grade, so we've restricted ourselves to that type of structure."

Q(D.S.) "I'd like to focus in on that correlation. The correlation is acceptable, but is it really the soil gas and source strength? Or, is it that plus the transport in the sort of homogeneous conditions found in all your houses? We are getting closer to the "radon availability index". The reason that you got a good correlation may be not only that the soil gas level is related, but that it is available because of the transport ability."

A(M.K.) "I agree, and we might want to follow the dual method Alan Tanner suggested which measures soil permeability as well as sour strength."

Q( ) "How many alpha track soil measurements did you make?"

A(M.K.) "We did one per house for about 3000 houses."

Q(T.T.) "Where did you put it in relation to the house?"

A(M.K.) "It's fairly close to the slab, perhaps three inches away 12-15 inches deep. We also take scintillometer measurements at that same location, and at a location on the opposite side of the house. We've seen substantial variation between the two sides of the house in those instantaneous radiation measurements."

C(W.L.) "Someone commented this morning that you have to go down at least a meter."

C(A.T.) "I did some work in Hillsborough and Polk Counties in Florida, where the [radon] problem is the worst, and Florida is really quite unusual. Often one will find 10 or 20 feet of well-sorted (in other words, the grain size is fairly uniform) pure quartz sand, in other words, a very uniform, homogeneous soil. The soil is of pretty high permeability -- it's pretty fine stuff, but it's well sorted. The diffusion coefficient is probably very characterizable and the permeability is reasonably so. The water table can come right up to the surface, or it can be down a ways, so there will be seasonal changes in dryness and wetness. But in comparison with most areas of the country, the soil is the ideal, almost the physicists' mode of homogeneity. Under those circumstances, placing track detectors at that shallow depth is probably not unreasonable. At some point I'd like to get into a discussion of the use and abuse of track detectors."

C(D.S.) "It is important to say why measurements agree or disagree as we discuss these points."

C(R.S.) "So, Alan, you're saying that it's not surprising that one sees some degree of correlation, at least at a gross spacial scale just because it is so uniform. David made the point earlier that if it's pressure-driven flows into the house (and of course you're not really seeing that with alpha track detectors buried in the soil -- at best you're seeing diffusive radon."

C(A.T.) "This may be the time to talk about alpha track detectors."

Q(T.T.) "Is it true that the bulk of your studies in Florida is on tailings and reclaimed pits?"

A(M.K.) "We're actually doing uniform coverage of the state."

Q(T.T.) "I was down there in the early seventies to study housing built on a reclaimed pit. I was surprised to find that my hotel room in Lakeview was hotter than the housing I was studying.

Q(D.S.) "Are there other experiences with the use of alpha track soil measurements?"

A(I.N.) "When Teradex first came out of these kits, we sent them to 60 homeowners in central New York, and put four monitors around each house. It was very simple and inexpensive. Simultaneously we put three alpha tracks in the house itself as well as in the water, in their toilet. We found absolutely no correlation of any of the radon measurements in the soil nor the indoor measurements.

Q(D.S.) "Can you give us some specifics as to the placement in the soil?"

A(I.N.) "It's the same technique: 12-18 inches into the soil, about three feet from the foundation, as specified. This may not have been a good idea."

Q(D.S.) "Tom Peake, could you speak on this issue?"

C(T.P.) "The office of Radiation Programs of the EPA has a program called the House Evaluation Program. We are taking some work that ORD is doing with the research in mitigation, and applying it to the private sector. These houses provide us access to homes which have been fairly well diagnosed. We're taking some soil gas measurements around the houses, 4 to 5 feet from the foundations. We are using grab samples, similar to what Alan has been doing; he's working on a soil gas protocol for us. We're taking the information which he's giving us with help from Jay Davis. We took measurements near houses and away from houses, three ft. and 15 feet. We found generally an increase in soil gas concentrations away from the house. We did not get a good correlation between radon soil gas values and indoor Rn levels though correlations were positive. We had one house with 550 pCi/L in the basement, and an average of measurement of 800-900 in the soil, 15 feet away from the house. Maximum levels were higher than that."

Q(D.S.) "Do you have alpha track measurements as well?"

A(T.P.) "We have some alpha track measurements, but results are not back yet. We had some problems with moisture condensation on the alpha tracks. And I know Charlie Kuntz from New York had trouble with the water table going up into the alpha tracks. We also had trouble with atmospheric dilution because of the way the dirt is settling."

C(M.M.) "Tom brought up that in making alpha track or charcoal measurements, in fact any type of soil-gas measurement, one has to take into account the influence of the house. He noticed that soil gas radon levels increase with distance from the house, and that there is a lot of variability."

C(R.S.) "Looking at Figure 9 of a house, we see where grab samples were taken from a soil probe, usually a meter of 1.5 meters deep. We see levels of 300-500 pCi/L at one point. Around the house the house the numbers vary to 89,000 pCi/L. Back fill questions, location of concrete slabs, and other factors account for three orders of magnitude variation."

Q( ) "Has anyone taken soil moisture content measurements at the same time that they took soil radon gas measurements?

A(A.T.) "I can show some related material."

Q(M.M.) "Let me use that question to take a step into another area, still dealing with soil gas measurements, but in the area of mapping of radon soil gas. The question is mapping radon soil gas permeability and moisture and how these relate to one another."

Q(R.S.) "Another question: You've been taking measurements, both alpha track and grab samples, and you've discussed confounding variables, such as moisture. Could someone comment on what other confounding variables might affect the placement or depth at which you grab a sample?"

A(R.S.) "If you get down below a meter or a meter and a half, you lose that confounding variable, except in really permeable soil."

Q(D.S.) "But Rich, could you comment on other confounding factors. We're talking about diagnostics, about how you can get really meaningful measurements. One factor is depth of placement and another is water and the water table and how they affect the measuring device. Are there others we should point out now?"

C(A.T.) "Not just the depth of the water table, but the percentage fractional saturation of the pores is an extremely important factor in both diffusion coefficient and permeability."

Q(D.S.) "Is there an estimate as to how these connections are made?"

A(R.S.) "It's important to note that moisture does two things: it increases the emanating fraction (or emanation ratio, if you want to put it that way). But at large enough moisture saturations in the soil, it decreases convective flow through the pores because as you begin to fill up the large pores, you lose your convective flow pathway."

C(A.T.) "These data are actually Roger's...the moral of all this is the following: In theory in dry, porous media, the diffusion coefficient is independent of pore size and the grain size, as long as you're within the mean free path of radon, which is quite small. But in the real world, the diffusion coefficient drops rather dramatically as you, (looking at chart: these are all orders of magnitude now and this is the diffusion coefficient in free air)... as fractional moisture saturation increases, you get a change in the diffusion coefficient of four or more orders of magnitude. Even in principle, you get the same drastic change in permeability as you increase the moisture concentration, and both of these are strongly affected by... if you were to think of the water in the pore space as merely occupying the space the air would otherwise be in you'd have a curve that went something like that... and only when you get down to nearly complete saturation would you have a marked change in diffusion coefficient. The answer is that the water, via surface tension primarily, tends to block inter-pore communication, and therefore the water has a disproportionate effect.

"Now I can get back to the question of alpha track measurements. I have to say that my views are not necessarily those of the Teradex Corporation. This is an experiment conducted by Willashevitz and Pyrictonov in 1959: they had a sealed tube, with ports for examining the concentration of radon in an open space, but in this otherwise closed tube, at various distances along the length of the tube. It was radium-loaded sand, and a measured diffusion rate d/porosity measurement of .0134 cm2/second, and these data were taken at steady state. Now think of this as a track detector cup over a column of earth. What it shows is that the track detector cup to some degree is actually performing an exhalation measurement on that porous medium. This .0134 cm2/sec is a fairly good diffusion coefficient, not quite as high as that of nice dry sand, but it's a good deal more than that of a lot of sandy clay loam; for instance, in which the curve would look much more like this... The implication here is that as the moisture concentration varies, the concentration of radon reflected in the track detector measurement is going to vary considerably, even though the actual radon production and the radon value in the pore space is remaining constant, or even increasing slightly. So, you do not get a real concentration measurement using a track detector in the ground, or in a porous medium. Now there is a modification here, because while this is a strictly one-dimensional situation, in real life there would be contributions from the side. So, the situation would not be as drastic as implied by the experiment. But you do have to remember that you are looking at a cross between a concentration measurement and an exhalation measurement that is going to be very drastically affected by moisture in the ground, and which is going to show seasonal variation and variations due to sudden precipitation and so forth. The closer you are to the surface, the worse the situation is going to be."

Q(M.M.) "Let me ask you a question about the moisture effect on the alpha track. Your chart shows some concentrations differences based on moisture. What scale are those? Are we talking about differences of 10% as moisture changes, or are we talking about 50%?"

A(A.T.) "I would think that changes of 50% would be more typical."
Q(M.M.) "Would you say then that based on that and on typical moisture ranges that the alpha tracks would not be a useful tool?"
A(A.T.) "There are two considerations. One is how you use it, and another is how you interpret the information you obtain from it.

"There is even another caveat, though, an important one: this study was done for completely different reasons by Chrisjensen and Mumquist, and what they had here were results from two holes side-by-side, and the one on the left-hand they made track measurements where the cups were used at successively greater depths, and back-filled so that there was no competition from the atmosphere, i.e., no atmospheric dilution. In the depth range down to six meters they have (although there is a lot of scatter in the data) a monotonically increasing radon concentration with depth.

"In the left-hand experiment they had the track detector mounted in a thimble that could pull up out of the ground after the experiment. That's rather difficult to do and Charlie Kuntz, in his presentation, had a control over the atmospheric dilution.

"In the right-hand experiment they merely drilled the hole to a given depth, put the track detector in the bottom and did not back-fill it behind. What you see is that as you go down in the ground, the permeability decreases, both because of moisture increase, and because of increased packing of the ground with depth, and the atmospheric dilution takes over, so that you get very low results. This is strictly an artifice, and means nothing. If you put track detectors in the ground, you've got to back-fill them. I was thinking about what happens when the track detectors are sampling a variable information volume. It may be that that's a saving grace and in fact a pretty good way. It's been noted for a long time that track detectors are an integrating device, and integration is general for soil measurements is very desirable. There are some data indicating that there is a seasonal effect of a factor of five. But, if in fact, the measurements from the track detectors are a function of variation in permeability and in the diffusion coefficient, maybe that's a good thing, maybe you do iron those things out, and get a better measurement. The one thing I would advocate is that people reduce the size of that open space. This may cause trouble with moisture on the surface of the track detector, but I think that it's worthwhile to consider experimenting with something smaller than the typical track detector cup.
C( ) "There have been some studies done comparing grab samples, alpha tracks, etc. I have here a Swedish paper which describe traverse with charcoal, alpha tracks and then the grab sample. From the information it looks like the different instruments measure the peaks at the same place. However, the magnitudes of the peaks are different in every case. So, I'd like to caution everyone that even though it looks as though these different devices might have some potential for measuring radon soil gas, only the grab sample can be used to get a permeability measurement which is important. Also, we should remember that when someone says they've measured soil gas measurement of 1000 pCi/L with an alpha track detector, that may not mean the same thing as the same measurement made with a grab sample.

Many people have been using a classification method developed by the Swedes, under which an area with 1350 pCi/L would be considered a high-risk area. We don't think that we can use that method as is. In the near future we hope to compare some of these different types of measurements around houses among themselves. We've already had a contractor do a little work, and his results are similar to the Swedes: that different types of instruments can be used, but that one must be careful about the configuration of the instruments and their use in different situations. We need to improve the protocols for the use of these instruments, because at the present time everyone is using them in different ways. We need to know how these different measurements relate to one another."

Q(M.M.) "That's a good point... we've talked about the direct, Lucas-cell type measurement, and about alpha track measurement. There's a third, fairly common type, which is the charcoal canister. After we discuss that a moment, I'd like to see if we can agree on a standard soil gas and soil permeability technique, based on the experience we have among us in this room. Which is the most simple, best technique?
Would someone like to comment on the use of charcoal devices for soil gas measurements?"

A( ) "Why don't you talk about Vern Rodgers' experiments?"

A( ) "In essence, Vern Rodgers compared charcoal canisters to track etch and grab samples and found that data from the charcoal canister (the same ones we use indoors) did not properly represent the levels of radon actually found in the soil because the charcoal canisters acted as a sink for radon. You weren't measuring the actual behavior of the soil. The Swedes, in the paper cited earlier, found that charcoal canisters gave the lowest soil gas concentrations of any of the methods. Moisture can also be a problem with charcoal canisters."

Q(M.M.) "Were these side-by-side measurements for which the charcoal canisters gave lower values than the alpha tracks?

A( ) "There's also variability in all the measurements."

Q( ) "How much lower are the readings from the charcoal canisters?"

A( ) "20-50% less would seem typical. It's not that charcoal canisters can't be used -- it's the way they are configured now."

Q(M.M.) "What is standard canister out there now?"

C(R.S.) "If you dig a hole you can put a pipe in the ground more easily. If you have a major soil gas radon concentration why not use a grab sampler or something? You can do it, because you can put a pipe in the ground just as easily as you can dig a hole."

C(A.T.) "The contention there is that you have temporal variability. How do you get around that?"

Q(T.B.) "We've talked about grab samples and alpha-track detectors. What happens with soil gas concentration as time goes on and how do we get a handle on that?"

A(W.B.) "It appears that seasonal variations are stronger than day-to-day variations, at least as compared to indoor radon levels. That seasonal variation is going to have a lot to do with where you are measuring. If, for example, one measures where the soil is frozen for six months of the year, soil gas values will be higher. But in the summer, soil gas values will be lower. It basically follows the same path as indoor radon levels. For instance, you would get very different soil gas values in Florida, where the soil does not freeze, than you would in New York or Pennsylvania. We have to watch out for freeze and thaw conditions because of elevated soil gas levels.

C(D.S.) "I'd like to interrupt. We're trying to address the accuracy and precision of different approaches, including alpha track, grab samples and carbon canisters. I'd like to outline how good those measurements are. We've tried to address some of the confounding variables. There may be more variables confounding carbon measurements than the other methods. We also heard about the short-term vs. long-term integrating effects of these methods. Let's try to keep the discussion focussed on specific points before we move on."

C(M.M.) " To finalize our discussion of soil gas measurements, I've heard several discussions about differences between the three techniques. About five months ago in Washington there was a meeting of people heavily involved in making soil gas measurements. We agreed that the simplest and most straightforward method is the direct measurement. I think Alan was touching on that when he suggested that a pipe be driven into the ground. The direct method is the most representative and gives a real value. One disadvantage is that it doesn't give you information on time variability. Another point is that once you have a measurement of Radon in the soil, there still remains the question of how easily the radon can move or migrate to a structure. In short, we mean permeability. Can someone factor those two together for us?"

A(A.T.) "Well, they are the factors. Permeability is not the only one of course; diffusion is a valid method of motion, and I think that because of the aggregate below the slab, diffusion may in fact contribute more than we think to the reservoir which that aggregate layer makes up. The process is then diffusion into the reservoir and then when you get an underpressure in the house, you pull that quickly in by flow."

"You can characterize the undisturbed ground with respect to radon availability being a product of radon concentration times the mean migration distance, by whatever transport mechanism. Does that tell the whole story or do you have a two-part problem, one of getting the radon to the subslab reservoir, and the second of getting it into the house? By assessing the first, do you get a handle on the whole picture, or not? In time the Berkeley people will give us the coupling coefficients."

C(M.M.) "I think the variability we're seeing between soil gas levels and indoor levels definitely says that the second process may be a major factor."

C(R.S.) "As Brad pointed out in his discussion this morning, it is a coupled problem. You've got the impedance across the building shell, and the impedance of the soil. That means that just knowing where the radon is high in the soil is not enough; we have to know at which points the radon can gain entry into the building."

Q(K.G.) "What about some of the soils we tend to find in this area which tend to be heavy clay and wet? You can pull a vacuum with a hand pump when trying to take a gas sample... as a matter of fact, if you take repeated samples, you can see the radon concentration go down as you deplete the source. How do you measure the soil gas concentration there?"

A(A.T.) "If that, in fact, is the location of the radon source, then you don't have a problem."

C(K.G.) "What do you mean we don't have a problem - elevated radon levels are present?"

C(R.S.) "Alan's point earlier was that if you have a diffusively driven reservoir, the house pumps on it in a diurnal cycle reflecting the fact that the indoor-outdoor pressure difference flows a diurnal cycle. We see that the reservoir may be depleted in one part of a day and replenish itself in another. This may explain what's going on near houses where the soil is of low permeability but where there is a reservoir under the soil."

Q(A.C.) "Do you see a diurnal change in the level of the reservoir?"

A(B.T.) "We haven't see it yet."

C( ) "But in one slide you showed in Philadelphia did show a time-varying soil level."

C(R.S) "But the frequencies didn't match."

C(A.C.) "Well, then your facts don't match your hypothesis. I'm not saying that was the situation at that particular house but rather that it is a plausible explanation for some house situations."

C(T.B.) "The problem is that you've sampled using a small hole about a meter deep. I might come in and excavate all that impermeable red clay off the top, and discover that four feet down is a layer of shattered shale which you've missed. We don't have x-ray eyes; soils aren't uniform and isotropic. All our models are uniform and isotropic, but if you were to make a finite difference model, I could imagine many soil configurations that could give you some very anomalous results. I see that occurring time after time."

Q(AC) "Have you considered going through the slab and measuring soil permeability below the slab?

A(K.G.) "Yes, on that house we did just that, and there was no permeability under the slab."

C(T.T.) "The way I've accomplished that over the years is simple, but requires a back-hoe. I just dig an eight foot trench, get down in the bottom of it, and I take a flux measurement through the bottom of the trench. The soil gas doesn't tell me anything. I've mapped it, I've tried to correlate it with indoor concentrations. I've used pipes to measure it at various depths in the same hole. I really question whether these soil measurements are getting us anywhere."

Q(M.M.) "Let me see whether I can put this in a final question then. Do we feel that soil gas measurements are a useful, viable and cost-efficient tool for diagnosing radon at a site?"

Q(A.S.) "What is the question which soil measurements are answering?"

A(W.L.) "Radon availability."

C(A.S.) "That's more than soil gas then?

A(A.T.) "Yes. I think a soil gas measurement per se can tell you something

only if it's very low or very high. But without the permeability data the procedure is highly questionable."
Q(W.L.) "This is where the question of nomenclature comes in. In Montgomery we agreed that the product of two factors defined the entry rate. They are radon availability and transport efficiency. Transport efficiency itself is a function of soil permeability, pressure differentials, and so on."
Q(T.B.) "But how could we discover irregularities in the composition of the soil, for example, pockets of sand, using soil measurements?

C(another person) "Don't forget that the ratio of surface area to volume for clay is very large, so it gives very high emanation efficiency for the radon. The transport efficiency is clearly very poor, but put the clay next to a layer of sand, and you can get the transport."
C(W.L.) "The soil gas measurement is very close in my mind to the radon availability. But without these other factors the situation is still very hazy."
C(A.T.) "Wait a minute -- I don't believe we've agreed that radon availability is the value of the radon concentration in the soil gas. When I say "radon availability" I'm very definitely including the soil permeability, the diffusive and advective flow, in addition to the radon concentration in the pore space."
Q(R.S.) "How then do you factor in the radon migration? How would you handle your definitions for a house which is pumping radon from the soil?"
A(A.T.) "I define it as radon concentration in the pore gas times the mean migration distance, which incorporates both the diffusive and the advective flow. The computation of that may be subject to change. The concentration of Radon alone is not a sufficient criteria."
C(E.K.) "I'd like to go back to the charcoal. When we developed the charcoal method in New York, we meant it to be used indoors, at comfortable temperatures. Using it outdoors raises a series of new questions."
C(M.M.) "I'd like to sum up by noting that we're not certain how useful soil measurements are at predicting radon problems at a given site. I think, though, we are in general agreement that the most effective measurement of soil gas is the direct measurement, and that we need to know the permeability of the soil. "
Q(   ) "What is the progress that we are making on soil gas sampling?"
A(A.T.) "I think I can answer that question and the one that Mike Koontz raised when he asked whether soil gas sampling was a viable technique evaluating radon problems on for a single lot. I think a good deal of progress has been made. A lot of measurements have been made, and I don't think there had been a lot of measurements before last summer...well, certainly there have been some, but there have been a lot more since. New York State ERDA(?) has done a lot of them, Jay Davis has done a lot, LBL did a lot last summer. I do not think it's going to be viable on a single lot basis, because in any given area you have to develope confidence that you're getting statistical validity in your measrements. You can't afford to make too many measurements on a single lot before it gets less expensive

to build the house the right way in the first place. But if you're talking about a development that mayt encompass a couple hundred houses and some acres of land, and you can afford to grid and spend several days doing it, there may (or may not) be a viable technique there. I don't think we have enough information at the present time to prove that. It will take a full year or so of gathering data to indicate the variability of a set protocol, whosever it might turn out to be. We have some indication that the results are going to be highly variable on a single lot. If we saw the same variation that Brad a Terry were talking about as a general rule, I don't think it would be a viable technique."

Q(H.T.) "What is the mean migration distance you've been talking about?

A(A.T.) "It's the distance which radon moves, by any transport process or combination of them, in it's mean life, which is 5.52 days. If you will look in either Clement's thesis, or in Sherry et al. in 1984, 'Factors affecting Radon Transport in Sandy Clay Loam' in Journal of Geophysical Research (the published 1974(?) JJR(?) article doesn't contain the equation), you'll see that the J, the exhalation Current Density under steady-state conditions is equal to gamma times the square root of the diffusion coefficient times the porosity times the decay constant. Gamma is equal to beta plus beta squared plus one. Beta is V over 2 times the square root of D epsilon Lambda. It's a mess! Multiply that by 5.52 days and you've got it."

Q(D.H.) "I'd like to step back again. The first talk with Mike was a very general survey over a land area, looking to see whether it showed signs of having problems. Then we went into very a very detailed analysis of the many different ways we could sample radon in the ground, and then we came back to the conclusion that a direct measurement (for instance, a grab sample out of a hole) was the best way of getting local information. Now I think that you've just stated that you would be afraid to use that technique for a given building-size plot, but that for a larger plot you could. Are we back to the simple surveys where we started out? We started in the big picture, and then we took this very detailed method and showed all of the things which Terry was pointing out, with different types of sand and everything else. But we ran into trouble in the small picture, and we're back using this very detailed measurement, but on a larger scale. Aren't we competing now with much simpler methods?"

A(A.T.) "Well, No. When you're talking about the gamma survey or the use of the NURE data or regional type information, when you're talking about square miles and larger areas, all you're going to do is to predict that most of the houses are going to be fairly low or else threatened enough that one should use radon-resistant construction methods. You can't make predictions about what the radon will be in any individual house. When you start talking about sampling on a given lot, then you're trying to be specific about whether or not you're going to have a radon problem at a house on the site. You can't evaluate that possibility at all by taking a simple measurement of radon in the upper foot of the soil."

C(D.H.) "You sound leary of making measurements down at that small scale."

A(A.T.) "I'm not so leary of it, I just think that you may have to make so many measurements that the costs of testing can increase above $2000, which is already more expensive than most estimates I've heard for making a house radon-resistant."

C(M.M.) "The National Association of Home Builders says that builders can build radon prevention into a house for $300 to $400."

Q(M.M.) "We can return to this topic later, but for now we'll have to move on. We've talked about identifying soil gasses and measuring levels in the soil; now let's discuss how we can identify a problem house? Not a survey of a given area or a specific measurement for a lot, but rather, how can we identify already constructed houses that may have problems? I'd like to narrow this to screening techniques for now, and we can move to techniques for measuring radon in specific zones of houses a little later. Does any one have any comments on surveys to aid in identifying of hot spots?"

Q(R.S.) " Mike, doesn't it depend a lot on what level you're operating? I think that as Alan Tanner indicated earlier, if you have information such as NURE or other radiometric surveys, soil permeability information and other things, you might be able to locate areas where you would do more detailed surveys. I think it's fair to say that we're not there yet in terms of compiling all that information and putting it together in a way that you could, with some assurance, say that a given area has a problem and that one does not."

C( ) "But we've done it."

C(A.C.) "Yes, I also disagree with you, absolutely. I've taken the twenty-eight hundred readings in Maryland [that University of Pittsburgh has from Maryland], and I can tell you exactly which counties or parts of counties have a problem, and which ones do not."

C(R.S.) "But that's an ex post facto."

C(A.C.) "That's right. Now as far as I'm concerned, the people who are using the NURE data and who think that it's a great technique, when they are confronted with hot spots that we've found using other techniques, they have confirmed that they should have seen them, but they didn't."

C( ) "That's not entirely true."

C(A.C.) "They all come back and say, Hey! Clinton shows on the NURE map, but nobody mentioned it."

C( ) "But nobody looked for it before. The reason why the geologists haven't been able to find the hot areas is that they haven't looked for them."

C(A.C.) "I'll tell you the same thing which I told a geologist last week. There are twenty to twenty-five spots in the Reading Prong area of New Jersey, where the geologists who identified the Clinton Knowles area in 1971 as a good place to mine uranium. In that part of New Jersy there are twenty to twenty-five hot spots that he was on personally in 1971 which were as high in uranium content as Clinton Knolles, and every one of those should be as much a hot spot as Clinton Knolles, but no one has found them yet."

C(R.S.) "I didn't actually mean to get us started on this. I thought what that meant was the sort of survey information which the states generally have, and it's a one- or two-page document describing the kinds of houses, where they're located, and that in fact may relate to geological maps and other information. But housing characteristics, occupancy characteristics gives you some idea of the level of concern we should have about the houses in this area. Is that a valid set of survey information? It's readily available for most states, and part of existing programs. How much of that do we as people interested in finding problem houses and fixing them should we try to solicit? Another source of readily available information is University of Pittsburgh Data."

A(R.S.) "What I was starting to answer earlier was the question of what sort of screening surveys we should do first. Is that what you were asking?"

Q(M.M.) "Let me rephrase the question. I was specifically talking about the screening survey. Given the fact that we have some information, whether geological or NURE or whatever, that would focus us on some area in a given state, what is the next step in identifying radon problems in given houses or groups of houses in this area? I'm talking about specific surveys, making indoor measurements. These are the data that Chuck would later used, and it's been generated in a random way, Bernie Cohen's data."

C(R.S.) "One of the things which you've started to do, a step in the right direction, is to wintertime charcoal screening surveys. They don't tell you anything about the annual exposure, but it could tell you something about hot spots which you can then correlate with external information."

A(A.C.) "In looking at 16 states, at least 12 out of 16 states had at least one county with at least 50% of the houses above 4 pCi/L. If I lived in a county in which 50% of the houses measured above 4 pCi/L, I would certainly have my house tested, and every house in that county should be tested, there is no other way to tell the extent of the problem."

C(R.S.) "That's right, I think you could use that as a gross screening survey, that someone would have to follow up."

A(A.C.) "The ten-state survey being done right now by ORP for the 2000 cannisters being run followed by 1000 follow-ups is going to really tell you whether those ten states have a problem and in which parts."

C(R.S.) "But it's very important to do it in the wintertime."

C(T.P.) "I'd like to say something about the surveys which ORP is working on. We're just now getting some of the results back from the state surveys, and we have only preliminary results. I'm not exactly sure how accurate they are. Using geological characterization, at least for Tennesee, we've been able to find geometric means higher in the areas predicted to be high.

C(M.M.) "So the state survey data may correlate with the areas predicted to be high. To be sure that this type of data is comparable, we need to standardize, to focus on standard measurements made in these houses. I'm not sure whether it has to be in the winter. It's true that doing it in the winter will give better closed-house conditions, but if you can achieve closed-house conditions, and if you can measure on lowest global levels, then you tend to maximize the values you find for a screening purpose, and your data will be pretty good."

C(G.F.) "Just a remark back to Chick's comment, I think New Jersey's approach in their follow-up, looking for another cluster situation like in Clinton, is mainly their fan-out program, when they have a discovery home or

an index house of 200 pCi/L. It's an excellant approach to find those pockets around the state that indeed have elevated homes in the vicinity. I don't know if Pennsylvania is doing that or other states you are in touch with, but even though it costs a lot of money, it's to find the pattern of high-level homes in a given territory."
C(A.C.) "Of the counties where I'm saying that 50% of the houses are above 4 pCi/L, most of them do not have any house with levels above 100 pCi/l. But the number of houses in the range 20-50 pCi/l are far higher than average."
C(T.P.) "When you do look at that data, you can bring that back to the geology of the area. I'm not saying that this could apply to a specific house, but suppose you look at a number of homes on black shale which is elevated, or suppose you look at a large number of homes which are elevated, and you examine the geology and the other information, you can use that to go and find other high levels."
C(G.F.) "We're sitting right here on a Triasic Ridge, and there was no comment made by state geologists a year and a half ago that this was at all a probable area for radon. So, I disagree with you on that."
C(T.P.) "The EPA has a national radon map. I've been looking at the data that goes with these maps, and the triasic basins are responsible for elevated levels, black shales are responsible for elevated levels, so I think we have to look into some of the other areas."
C(M.M.) "If we could stay off geology for a few minutes here. Gene was talking about fanning out around high areas once you've discovered them, and making additional measurements. That seems to be a good policy. Chick was talking about taking measurements in every house in the United States. That would tell us all we need to know." (laughter)
C(A.C.) "You've misquoted me."
C(R.So.) "We need to get the permeability better documented. This variable is jumping out at everybody, but there's almost no discussion of the methodology and protocols needed to pin down this variable. We should always have two parameters for each house. We keep describing a situation in which only one of two parameters is known, the other one is guessed, and the explanatory power is very low. People have been aimed too much at measuring radon concentrations."
A(A.T.) "It isn't that we don't understand it, we just haven't measured it. First of all, there is a data base, though it isn't all that we would like. Most counties in the U.S. have data concerning perk tests and soils information, or the Soil Conservation Service has information. The Berkeley group spent a long time studying soil groups and which ones had tendencies to be permeable. There exist very specific data, sometimes with very high density, on things like perk tests. They may not be quite what you want, but they do give you a strong clue. In the state survey effort that Tom has been talking about, those data are used as clues in classifying counties as high or as low risk. So far it looks as if it's working pretty well."
C(R.So.) "Fairly well" is the last word there. How much stronger is the explanatory power of geological measurement when you have these two variables instead of just one? We should be able to get a quantitative feel

for how much we can improve our explanatory power when we consider both of these variables instead of just one."

A(B.T.) "We do that under the slab. You take your grab measurement, we see how pressure fields develope, and you're basically measuring permeability."

C(R.So.) "The goal would be to improve the quantitativeness of these methods. The discussion in these last two hours has been non-quantitative."

A(A.T.) "The really missing variable, though, is where you are on the coupling efficiency between the ground and the house."

C(R.So.) "The third element is obviously how leaky is the house boundary?"

C(A.T.) "We're going to come to a solution to the first two before we figure out the third, I'm afraid."

C(D.S.) "Rich suggested that you needed winter and summer readings, some indication of an annual kind of situation. In looking at the Canadian survey, they only do summer measurements. They've come up with very low levels of geometric means. They have no problem, by their definition. In my opinion it is inadequate to make measurements in only one season".

C(A.C.) "In fact the highest level ever measured was found in June, closed house, on a dining room table, when temperatures were in the eighties and nineties, slab on grade house, a value well above 5000 pCi/L. The measurement in the wintertime was only 2000 pCi/L.

C(A.T.) "That soil runs several hundred ppm of uranium as well."

C(A.C.) "In fact the gamma measurements in the backyard got as high as 120, average at the four corners was about 80."

C.(T.T.) "I don't think we should overlook the value of gamma in a quick screening method either, I mean an on-foot micro-R-meter kind of survey. If you've got high soil gas you're going to see the bismuth gamma, you're going to see elevated background in a hot spot. If you've got gamma in any amount, you can bet that you'll find high radon in that area."

C(M.K.) "But if you have low gamma, you still can't tell that you don't have a problem."

C(T.T.) "Yes, but it will tell you right away where your real hot spots are. I've never seen an extremely hot house that didn't have a significant gamma radiation level associated with it. I came out of the Watras's house in my sport coat, and about 30 minutes later down in the valley I measured about 60 micro-R per hour, background was twelve to fifteen. It's a good quick screening tool to find the hot spots."

C(M.M.) "I've seen a fair amount of correlation between gamma and radon levels, and the correlation is better at high levels. The gamma seems to indicate the high level houses a lot better. Gamma seems to me like a useful tool for identifying those very high level houses. It may not be as useful for those houses which range in the 10, 20 or 50 pCi/L levels."

C(A.S.) "No, I would say that it is the other way around. Gamma may be useful for identifying regions, but as for identifying individual places (unless they are contaminated) it is not very useful."

Q(M.M.) "You're saying that gamma could grossly identify a region, but probably would not identify a single house?"

A(A.S.) "Yes, particularly when we're dealing with these very high houses.

Let me say that it seems insufficiently predictive for me to suggest it as a general rule."

C(T.T.) "Let me use an example to help me with my argument. We've got an area in Edgemont, South Dakota, where none of the houses exceed 30 pCi/L radon concentration. This was not the result of any mill tailings, but rather, occurred naturally on the ridge where the houses are located. The gamma is consistently 40% above normal background down along the streak where we've got these elevated houses. We're seeing the radon and the Bismuth 214 in the soil gas in an equilibrium."

C(M.M.) "So here the gamma is identifying even lower-level houses."

C( ) "The question has to be phrased very carefully here: are we looking for something to tell us not to put radon resistance into construction? Or are we looking for something to tell us to be on our guard for extreme problems after the fact? I see no evidence [that we've found] an indicator that says that one should not put in the radon-resistant construction. Yet we see many indicators here that tell us that we may be risking a very high house, and that we should be on our guard."

C(A.T.) "Let's take south New Jersey. It's in the Atlantic coastal plain, there are rather few places where it would be reasonable to expect that there would be course material to give you a permeability problem. The uranium series activity in the ground is quite low. You might want to say, 'Look out, boys, look out for some ridges of gravel that we might find sometimes; there you've got to take caution.' But otherwise this is an area where radon-resistant construction should not be necessary 99% of the time. The same thing goes for much of the outer coastal plain on the east coast. You get down to the Carolinas, then you've got to start worrying about Thoron. Unfortunately, the measurements being taken now do not detect Thoron--not that they can't, but routinely they try to exclude Thoron from consideration. I think that is going to be a mistake in some places."

C(T.B.) "If you get Thoron present in any large amount, you'll get a background which will last longer, and I haven't seen that any place. "

C(A.T.) "Well, so far I haven't seen Thoron greater than 30% of the radon count. But there are some places where it may occur, there they're known.

C(M.M.) "Let's move on now to visual inspection and questionnaires, out of the realm of source availability and into the realm of diagnostics. Visual inspection and questionnaires: what information can we gain by simply looking at the house and asking the home-owner questions about the house? That will give us information which we'll later use in developing mitigation techniques."

C(A.C.) "The LBL questionnaire which we were using both in New Jersey and in other places consisted of five or six pages of questions. The surveys simply give us a systematic way of looking at the most likely entry points for radon. Mary Cahill has made a few house visits with me, and I've walked through a house, spent a half hour in the basement, gone upstairs and sat down at the dining room table, and she was writing and I was helping. I can answer 90% of the questions there without going and looking. The reason is that I've been in enough houses and I've found enough cases where there are obvious radon entry points that I know what to look for. The best thing you've got is your pair of eyes. You often run into things that you had no way of predicting. We were walking through one house in New York when I saw a block of wood lying on the floor. I kicked it and it didn't move. When I picked it up I saw that it covered a hole in the slab. This was on an asphalt tile floor, and the block of wood covered a cleanout plug for a sewer line that went out to a septic system. The plug had never even been caulked in, and the soil was showing. There was no way to look for this sort of thing, it just happened to be there lying under a piece of wood. You can see holes in the wall without any problem. As Terry said this morning, if you can see dirt, you know you've got the potential for a problem. But you've got to constantly be thinking of places where dirt might be exposed, that you can't find. Arthur can tell you stories of floor drains which looked absolutely innocuous, not at all like they could be entry points for radon. After about a week of trying to find where that last fifty picocuries of radon was coming from, he tested the floor drain, and it was the floor drain without a trap, but drained to the surface behind the house, not connected in any way to an entry route. However, when he finally took his grab sample out of the floor drain that didn't have a trap, and measured the velocity of flow in it, there was enough radon in the gas coming out of the pipe to account for the level in the basement. There was a perforated drain tile all the way around the footer, and where that drain surface ran through or under the footer, they tied the drain tile into that line, and ran it to the surface. That was a good collection system around the house, the soil gas was coming up an innocuous line which had no perforations in it. Because of the drain tile arrangement it was dumping radon into the basement. It suddenly dawned on me a month ago that when I built my own house, I ran my three basement drains to daylight, and one of the three has never had any water in it. When I went out under the foundation with it, I remembered that I tied my footer drains from all around the house to that same kind of line, exactly what I'd seen in Pennsylvania. There's a source you have to look hard for; there's no way to know what is there. Even if someone had questioned me, I wouldn't have noted it, because I wouldn't have thought of it. In fact, it didn't even occur to me until a year after our visit to Pennsylvania."

C(A.S.) "Let me add to that. One home-owner told us there was no weeping tile drain around the house. I suspect he may merely have had crushed stone without."

C(A.C.) "Either way. There's some way that soil gas is getting in to that pipe and coming in. It used to be very common to put drain tile around the house, go in through the basement, and into the sewer line above the trap. Then they made it illegal to put storm water in with sanitary water. When you're looking at these houses, think of yourself as a gas, and look for any holes you might get through.

Q(M.M.) "In talking with homeowners and making visual inspections, what additional information could you gain for designing mitigation techniques for that house?"

C(A.C.) "As far as I'm concerned, the longer the questionnaire, the better. (laughter) This may come as somewhat of a surprise to your people, Mike, but I'd like to get that questionnaire down to two pages. The reason is that I'll pick up most of these things, [that home-owners write on their questionnaires] when I go through a house. But we have to think about the new people just getting into the field, not just the experienced people who've been through hundreds of houses."

Q(D.S.) "To put this in context, are you talking about a twenty- or thirty-minute walk-through, or about something which has been categorized as coming later, as part of the pre-mitigation surveys? At that point you need six- or eight-page questionnaire, you need all the information down in a systematic form."

A(M.M.) "I'm talking about a very cursory, preliminary visual observation of the house, and questions that might be asked of the home-owner."

C(D.S.) "That's the sort of thing that states often do. When they think they've got a problem, they'll visit the home and fill out a one- or two-page questionnaire. But that has limited value."

Q(T.B.) "Is this a questionnaire that someone takes out and walks around with, or one like those which Bernie Cohen sends out?"

A(M.M.) "This is a questionnaire like those which Bernie Cohen or the state might send out. We're not into pre-mitigation diagnostics yet."

A(A.C.) "These one- to two-page questionnaires have got to be so simple and explicit that even a home-owner who knows nothing about construction could understand it. You've got to assume that he knows the difference between a public sewer and a septic system, and that he knows whether he's on public water or a well. These things are important in this first phase: whether his house has a crawl space, slab-on-grade, or basement, or some combination of these; if he has a basement, whether it's block-wall or poured concrete. These questions have to be phrased so that the average homeowner, who knows nothing about house construction, will know what the question means and how to answer it."

Q( ) "What is the value of this type of questionnaire?"

A(A.C.) "When we're going to do an additional research project in an area, and we want to cover 20 to 30 houses, then we'd like to have 100 to 200 houses at the beginning to start sorting from. If we start out with 500 or so, then we can sort those into categories based on their substructures, or into other categories, so that we can aggregate like houses into study groupings. However, such a questionnaire does not help in the general mitigation effort.

C( ) "The point I was going to make is that the way houses are built no two exactly alike, if the soil gas is the same underneath, it really doesn't do you much good just to know the substructure of a house as far as telling you whether you're going to have a radon problem. You've got to measure anyway. At that point you've got to do a longer questionnnaire, of the type done before mitigation."

C(M.M.) "So the information which is to be gained here is simply the type house, slab-on-grade vs. crawl space or basement, and questions as simple as the type of walls, i.e., concrete block vs. poured concrete."

C(A.C.) "What kind of sewer, what kind of water, type of fuel, type of air circulation, which might tell you something about depressurization of the house."

Q(K.G.) "Isn't this the same idea that mitigators are already using when they prequalify a house by asking a list of about 10 questions over the telephone? This method has already been in use for several years."

C(T.T.) "There are about 10 key questions which really mean something to a mitigator. I have an example here, a letter from a man in Silver Spring, Maryland. I fixed his house 3500 miles away and asked him 10 questions. He wrote me a thank-you letter saying "I got [the radon] down from 16.8 pCi/L to 2.8 pCi/L, Thank you Mr. Tappan."

A(A.C.) "I did the same thing with someone in the western suburbs of Chigago, who had 10 pCi/L in his house in October. He did nothing but seal the basement. He called me back in January with 1.7 pCi/L."

C(M.M.) "We'll try to put those ten questions together and offer them as information to the group. One final question: It's a reflective question. When we're talking about a questionnaire, we have to be sure what its purpose is. I think we've been discussing several different ones simultaneously. The purpose of that ten-question questionnaire is to determine whether there is any action which the home-owner can take, short of calling in professional diagnosticians or a mitigation team. There are five or six questions which you can identify, so you know if there is anything the homeowner can try. Once we get beyond that questionnaire, the questionnaire in the next level is much shorter. If the home-owner has confirmed the measurements, or has tried sealant (which is generally what we're talking about here), the next questionnaire simply askes the name, address, phone number, and the date on which they are available. Any other questions are really placebos, to show that you know your stuff and are concerned about their house."

Q(M.M.) "This leads us to] the determination of radon concentrations in different zones of the house.... Another thing I'd like to touch on is the status of our scientific knowledge, our need for additional research: do we feel we've reached a point where we can define the topics we've discussed this morning? I'll let Wayne open that one up."

C(W.L.) "Let me pose one question for thought over coffee break. I come from a side of DOE which has been concerned with basic research. Until this morning I was thinking that we were going to have to do some detailed geological studies to develop better predictive models on a regional basis, to try to understand why certain mitigation techniques are effective; to understand all the factors which determine radon entry rate, so that we really have a firm scientific basis for making generalizations from the experience we gain in the field. However, the message I've gotten today is a little bit of a surprise to me. What I seem to be hearing is the fact that we have already developed the kind of qualitative understanding we need to be effective mitigators on a very broad basis, even though we can't put all the factors important in defining radon entry together into a coherent equation. I was very impressed by the success one speaker had, based on a very limited approach to the problem. If that is true generally, then perhaps there are just a very few questions on which we should focus our attention. That is, perhaps we need not develop a radically more detailed scientific understanding. Perhaps we are already where we should be."

C(A.T.) "There are 79 million more houses, aren't there?" (laughter)

Q(L.K.) "One thing which we haven't discussed, which affects your panel and the panel on post-mitigation diagnostics: how well we can relate a measurement which we do either before or after the mitigation to the annual average? This has certainly been one of the concerns in the houses in Clinton, and when you get a year's worth of data those houses are probably going to be under 4 pCi/L in an annual average. They're not below 4 now so you can't really say that they are successful. I think that one has to be careful that annual average exposure is really the number, and not the single measurement in the basement."

C(T.T.) "We have tried passive mitigation systems. In one case the levels stayed low to December when we hit a spike and we put fans in the exaust stacks. We probably overreacted and we would have been o.k. on an annual average."

C(M.M.) "So we realize that we need additional information. There are studies going on right now to help us translate fairly short-term measuremtns made under different conditions and at different times of the year to that annual average. Our goal is to keep the annual average below some given number."

C(L.K.) "So the groups who mitigate in the summer must know how low they have to get [the radon levels] so that it will stand up in the winter [for the yearly average]. When you're mitigating in the winter, you don't necessarily have to constantly stay below 4 [pCi/L].

C(R.S.) "But it's the real-estate market which is driving a lot of mitigation."

C(L.K.) "But if we have the data to back it up, to show that those numbers mean something... We can't tell them anything now based on one measurement, without an annual average."

C( ) "If you hire me to do a mitigation job, and if I bring it down from 200 to 8 PCi/L, and if your house is on the market, is that going to satisfy you?"

C(A.C.) "They won't sell the house."

C( ) That's right, and 65 to 70 percent of the mitigation in this state being driven that way. It's very difficult to get that point about the annual average across to the home-owner, especially when dollars and cents are involved."

C(M.M.) "Those are the facts of the real-estate market, and I've had to deal with it too. Thank you all, that ends this session."

Phase II. WORKSHOP DISCUSSIONS

PRE-MITIGATION DIAGNOSTICS - L. M. Hubbard, Chairman

C(L.H.) "First I would like to go over the order of the topics and the distinctions we will make between research and "real world" applications of diagnostics. Questions submitted ask what are the answers we are getting from the measurements we have been making over the past few years? Availability of the equipment; how easy is it to implement; and what are the costs involved are some of the other questions. A good example of how research approaches can be applied in the field was given by David Saum earlier in the workshop -- looking at subslab ventilation diagnostics. In what percentage of homes will SSV work successfully is another question to be answered. Questions about some of the most useful diagnostics, grab samples, both ambient and depressurized with a blower door, are often asked. Communication under the slab is a question that has already received considerable attention so perhaps it doesn't need much more discussion here. Tracer gas measurements, differential pressure measurements, soil gas flux measurements are all topics needing discussion. One question that has been asked is how can stack pressure be measured -- hopefully we will have time to discuss that question. Are diagnostics cost effective? I would like to hear from the mitigators on that question. Also, do the seasonal variations matter? I would like to begin with a few words from Wayne Lowder on research versus the "real world" diagnostics."

C(W.L.) "First of all I have been chastized by all the DOE contractors during the intermission for my remarks. However, my statement was just to stimulate discussion. (Laughter) There is a very important distinction to be made concerning the real world application of our current state of knowledge which derives from the research over the past few years. What I am hearing today is that this research has been very successful in pointing out the significant parameters: what should we be looking at and how we can simplify the diagnostics for real world applications. As we assemble many case studies of success, mitigating under some degree of ignorance, we need a scientific knowledge base in order to understand why we are successful in particular cases. In this way we can, with some degree of confidence, move on to improved procedures for a variety of circumstances. There is clearly a need for research, the EPA field demonstration program is a prime example, especially the study in New Jersey, which is a combination of the practical and the research aspects of mitigation and diagnostics. This is a very important effort.

I would like to stimulate the mitigators here to probe the questions -- do you feel confident that you will continue to be successful and what do you think are the needs for better information from the scientific community?"

Q(L.H.) " What diagnostics are useful to understand the radon mechanisms?"

A(W.L.) "We are really zeroing in on those factors in the environment that are relevant to radon entry rates in housing. The question of radon in soil gas is extremely important, since it surrounds the house, and supplied the "available radon". Its the soil gas that transports the radon into our houses and is the source for the indoor exposure. Permeability is the property of the soil that tells us, together with the differential pressure, the rate of soil gas transport. Maybe in a way we ought to define an idealized situation which will represent a figure of merit - a model house (or several houses) with properties that are well defined so that when you have a pressure difference across the envelope and you have certain defined soil characteristics and a level of radon in the soil gas, you have now defined the "source term" in this idealized situation. Whatever number you get is representative of a particular site even though it doesn't represent a real house, it does relate to the idealized set of circumstances. The real problem is there are so many variables, particularly within the house itself, you clearly can't develop a model (with a finite number of measurements at the site) that will define the radon entry rate at any particular time. So really it comes down to the fact that we have to understand the mechanisms involved and generalize from a particular case."

C(L.H.) "Let's hear from the mitigators".

C(R.Si) "What I have been hearing is that SSV achieves a high degree of success but that it is highly dependent on the conditions under the slab. What we are then dealing with is a very small percentage of houses where SSV doesn't work because of soil conditions. We are looking for an amount of suction that is going to overcome the radon flow into the house and redirect that gas flow. Some of the things we want to look at are the necessary forces to just what is necessary to remove the radon. Another item would be aimed at house without good communication under the slab where using a "small well", you might short-circuit the radon before it reaches the slab.

Q(L.H.) "What percentage of houses are not cured using SSV?"

A(R.Si.) "The percentage we have found is very small, i.e., only one or two houses out of a hundred. Even then it is often a question of fine tuning. Using dampers in the mitigation piping allows one to increase the suction where it is most needed. For example, with slab-on-grade it might not need as much subslab ventilation because of settlement in the area along the common wall."

Q(L.H.) "Do you use premitigation diagnostics?"

A(R.Si.) "The premitigation diagnostics are limited to a communications test, taking into account all the obvious things that have to be dealt with, working toward a mitigation strategy. In the case of limited soil porosity we would employ a collection pit area, something we have done for the Piedmont study. The number of pits would be related to the basement geometry and soil porosity."

Q(A.C.) "How big is the pit?"

A(R.Si) "Typically its a two foot cube, but we may include perforated walls and base to increase the effective volume to help draw in the radon gas."

Q(L.H.) "Bill, how much premitigation diagnostics are you using?"

A(W.B.) "Often it is just a walk through where we anticipate porous soils. In the early days, we would have used an air-to-air heat exchanger for radon mitigation but now that has become a less attractive option, as we now are removing those units and replacing them with subslab units."

Q(L.H.) "Do you use grab samples in your work?"

A(W.B.) "I do use grab samples occasionally to test for hot spots. If there is a question of communication under the slab I do use the vacuum test. That's really the most important test where I use the Magnehelic gauge to get actual pressures. Using smoke, sometimes it will not go down the hole even when you can get a gauge reading (sometimes after 15 to 30 seconds) with marginal communication. At other times the opposite is true, so you should use both methods."

C(A.S.) "Let me comment on the word "diagnostics". It is being used currently as being all things to all people. If we follow the medical theme, we know what disease these houses are suffereing from, it is "radonitis". It is "diagnosed" by making one measurement to show radon levels are elevated. The subsequent investigation that takes place is "pathology". We are looking at the approximate cause, but knowing the causes of a disease may provide no help in the treatment. Our scientific friends are involved in "pathological research". Mitigators are involved in "therapy planning". There is a sharp distinction between knowing the pathology and determining what can be really helpful. Subslab ventilation could be viewed as the penicillin of the radon world. If we can achieve soil depressurization we know the problem will go away. We don't need to know if people are running dryers or what the pressure deficit is in the house."

C(W.L.) "You don't even need to know where the hot spots are."

C(A.S.) "That's right. You probably don't even have to know much about the house."

C(R.Si.) "Probably the most time consuming item is how to get the exhaust pipe up to the roof."

C(D.Sa) "I agree with some of these statements, but its hard to say what percentage of the time you will get results by slapping something into the nearest convenient place. Perhaps 50% of the time. We certainly agree diagnostics aren't always absolutely necessary. I would like to go back one step. There seems to be some question what SSV is actually doing and what is its active mode that is actually solving the problem. I claim that suction on these surfaces prevents radon from entering. There seems to be some question if its the air movement that has something to do with this. I claim that if we could do a perfect sealing job and no soil gas came in from the upper surface of the soil that would be fine and that suction itself, with limited air flow, would be the goal".

C(L.H.) "I thougt the question was flow out of the mitigation system?"

C(D.Sa) "I don't think we have even really decided how radon comes into the house when good sealing is done. I am finding it's pressure driven flow through concrete therefore all my actions are to get as low an airflow as possible and as high a suction as possible. There are some people here that don't think that's right."

Q(A.C.) "We did have a little discussion during the break. But first I would like to ask if there is any significant passage of soil gas or radon through four inches of concrete, that has no cracks in it?"

A(D.Sa.) "I have made such flux measurements. Placing a box over what appeared to be crack-free concrete I noticed a build up of radon in the winter in the box, but in the summer time, with no pressure differential, the radon was not present."

A(B.T.) "In our flux measurements on concrete blocks and poured walls and floors, if you do the calculation, you can only account for a fwew percent of the indoor radon levels. These measurements would account for diffusion and microconvection and it is not enought to account for the indoor levels

that we see. A fine network of cxracks may contribute to the problem but will not be sufficient."
Q(D.Sa.) "There is a bit of contradiction here - why can't we seal and achieve our goals?"
A(T.B.) "We are digressing into mitigation. Knowing where it comes from is important. My experience has been with doing subslab suction with one pressure point in the corner. The experiment had other points open at the other sie of the slab, hoping to inducs cross flow assuming that was important. The more we sealed the better reductions in radon concentration we achieved. Thus we moved to higher suction under the slab and less airflow."

A second example is from one of the Clinton houses with a dirt floor crawlspace. We placed perforated PVC pipe in a grid on the floor and sealed the floor with a heavy polyethylene film - a that is transparent to radon by diffusion. Then we applied suction to the PVC pipe with complete success - the radon did not penetrate the plastic.
General Discussion: (T.T. D.Sa. R.S., T.B., etc.) The goal is to reverse the pressure gradient, flow is not the important feature rather it is the fact that flow is from the substructure into the soil. The establishment of a slight negative pressure is all that is needed.
C(A.T.) "NBS has been trying to develop a portable radon source using a thickness of polyethylene where half the radon decays prior to passage through the film (13 to 16 mills). Ron Colley and Robin Hutchinson are the people to contact."
C(T.T.) "We use radium ore inside a plastic covered bucket as a method for evaluating materials. It's amazing how many plastic materials that radon moves through."
C(T.B.) "Diagnostics reveal how good the communication is under the slab. The presence of a good gravel base or soil separated from the slab means that one can often be successful with SSV using a single suction point even on the basement perimeter. In other cases, spotty suction is evidenced (in one direction for example) and in clay there may be no influence beyond the suction point. Powdered soils may indicate little communication using the vacuum cleaner technique yet frean may pass through them. SSV systems thus may still prove successful. At the fine end of the soil particle size range, basement walls may become more important as a radon source. Freon is very slippery and can move quickly through even fine soils with the suction in place."
C(R.S.) "One justification for further research is that all mitigators indicated they have installed systems that don't work the first time."
Q(L.H.) "Where do blower doors play a diagnostic role? The usefulness of blower doors relates directly to the application. If SSV doesn't work, then the BD may have application to radon mitigation basement pressurization, heat recover ventilation, or subslab pressurization."
A(R.Si) "We used blower doors for subslab system evaluation but we have abandoned that approach. The question is where do you use the blower door? We have a high confidence that with one hour of diagnostics we can tell whether SSV systems will work, without use of a blower door. If SSV won't work, then what is the next best mitigation method? More direction on that point may involve the blower door. Heat recovery ventilators, basement

pressurization, subslab pressurization are some of the candidates for the second best strategies."

A(T.B.) "The blower door is useful for sizing the fan for pressurizing the basement. The fan must be small enough so that a large energy penalty won't be paid (same range as normal air infiltration, i.e., less than 300 cfm). One also wants to avoid too much suction upstairs which can cause problems in down drafting combustion appliances. Sealing between basement and upstairs reduces the required air flows."

A(I.N.) "The blower door applied to SSV system diagnostics has proven to be helpful to evaluate basements under extreme conditions, e.g., simulating winter stack effect conditions to make certain SSV will be effective throughout the year. We have examples where systems failed under winter conditions but were fine in the summer."

General Discussion: Concerns were expressed as to what level of depressurization assured that the SSV systems would work for all seasons. A degree of consensus was arrived at. The house is a box, with the volume under the slab another box. The important point is that there are pressures in both boxes. A rule of thumb such as pressure differences at least 0.015 to 0.03 inches of water (4-8 Pascals) would appear sufficient for SSV success."

C(K.G.) "Movement of the neutral plane by controlling air leakage sites (via sealing) of the upper portions of the house can also limit the stack effect and thus make the radon problem less severe (and the SSV requirements less stringent)."

Q(L.H.) "Again do we have any additional answers to the question: Is the BD useful in evaluating SSV systems?

A(M.Me.) "We haven't been able to make the blower door do the SSV diagnostics job, but the "blower floor" has applications in this area. What about the use of the blower door to assess leakage areas for HRV's?"

A(A.S.) "The best application of HRV's comes as a result of changing the distribution of the air flows in the house and not the general level of ventilation achieved. Dilution effects are limited to two or three times normal ventilation rates. By sending the air upstairs, much more can be achieved. BD measurements can help resolve air leakage for different zones and thus help the mitigator make the right decisions."

Q(L.H.) "Taking grab samples around substructure under different conditions (ambient, pressurized, etc.) is one diagnostic approach. How useful are these techniques based upon recent research?"

A(B.T.) "Depressurizing, and taking grab samples does seem to bring about radon movement similar to winter heating season conditions. There is a question as to whether this would be true in all homes. There are also changes in the radon levels in the soil to confound the issue."

A(R.S.) "Pressure differences are due to stack, wind and appliances. Wind pressures are directional, thus influencing the soil on different sides of the house. Ventilating the soil is also possible due to the wind. Using a negative 10 Pa standard test applies a 'research base'. Measurements on walls, floors and piping in the mitigation system add to our knowledge."

Q(B.T.) "Grab sampling is a integral part of the radon research; do commercial mitigators see this as a useful diagnostic approach?"

Q(D.H.) "Isn't the depressurized condition for grab sampling the more

useful approach and should this be the appropriate standard? Remember it again takes time to reach equilibrium after the start of depressurization."
C(K.G.) "Clearly the most recently tested house in the Piedmont Study showed combinations of wind pressure and return duct leakage that caused negative 10 Pa basement readings."
Q(D.Sa.) "What about the situation of entirely different results when applying the negative 10 Pa to two houses? One shows a radon concentration dropping to zero; the other a large increase in radon levels."
A(D.H.) "What is entering the picture is the radon source characteristics. In one case you have a condition of a limited radon source which is rapidly depleted. In the other case you have a large radon source where the soil gas has reasonable transport into the house.
C(A.T.) "The vagaries of different soils immediately around the house, the location of openings through the basement walls, and the effect of freezing soil cover in winter may all influence the amount of radon entering the house. Also local freezing could plug off leakage sites."
Q(D.S.) "Hollow block wall convective loop air movements were evident in some of the testing -- could we hear more on that subject?"
A(B.T) "Again depending on the air movement in the blocks, outside air ingestion can mean a local dilution and reduced radon concentration. In other situations more radon was drawn from the soil and concentrations rose inside the blocks during depressurization."
C( ) "At this point the use of negative 10 Pa as a standard diagnostic procedure is inconclusive, although it would appear to be useful much of the time."
Q(D.Sa.) "How good are grab samples under ambient conditions? Although I have only been in the mitigation business for seven months I have assumed grab samples from under the slab to be relatively invariant over the year. Sampling in walls has been limited in our houses."
A( ) "I have concluded that grab or continuous sampling under the slab is invaluable since one must match the final pressure field to cover the high level radon sources. Relative distributions are basic, and if these were changing seasonally this would erode confidence in the approach."
A(B.T.) "In the seven LBL homes we have the ability to measure subslab radon concentrations when mitigation systems are turned off as well as the continuous measurements in the control house. Variations are observed."
C(L.H.) "Variations over 24 hours are another problem with grab samples as well as spacial variations."
C(R.S.) "Less diurnal variation is found in the radon concentration under the slab than in the basement, for example. For most houses, I don't believe grab samples are very useful. However, with more difficult situations, e.g., subslab lacking communication, grab samples may answer vital questions."
C(L.H.) "With mitigation systems in place, continuous readings illustrate SSV altering concentrations in the wall when they are turned on because of communication between wall and subslab and sweeping of basement or outside air into the wall dilutes what was the higher radon concentration zone."
Q(L.H.) "Tracer gas methods, where do they fit in?"
A(T.B.) "One application is the use of freon. The freon tracer moves under the footer to indicate drainage paths."

A(B.T.) "In Portland tests, tracer gas (SF6) was injected in the yard (via probes at different distances and depths) and monitored continually for the level of buildup in the house. Transit times were measured, coupled with a pressure field map (depressurized the house and looked at pressures and probe points around the yard) to see if gas movement correlated with the pressure fields."

A(T.T.) "We have traced air flows over an entire slab using freon tracer looking at details of the flow paths."

C(D.S.) "There is a question whether tracer gas should be reserved for problem cases and not used as a premitigation diagnostic tool." Perfluorcarbon tracers are another candidate for tracer methods."

Q(R.S.) "SSV does seem to work in many situations. What concerns me is whether these systems continue to perform over the long haul. Will the systems receive proper maintenance? We are mitigating hot houses with mechanical systems -- is this the way to proceed in the long haul?"

C(D.S.) "Durability is an important consideration, partly the reason the diagnostic list was more complete is that we need backup strategies. The government and other interests represented here can't just say that we don't know what to do for 10 of 50 houses based on public health. We need backup mitigation approaches, and backup diagnostics. That is one reason we have been discussing blower doors. What are those other options and how are they going to work? Even though SSV appears to offer an acceptable solution in a high percentage of homes, that is not enough. We need other options. Over the 20 year time frame we must consider cost effectiveness. Once we have defined cost effectiveness we must fill in some of the options that have only been discussed briefly."

C(A.C.) "What we are looking for is a fail safe technique. It doesn't matter if it is mechanical or not, but one must know when it is working. In the Washington, DC area one group is using a five dollar switch to indicate when suction is lost and a warming light will be activated where the homeowner can see it -- you do not have to go down and read a gauge. Remember a passive system can be overwhelmed and the homeowner not even know it is failing to do the job."

Q(T.B.) "When do you know when to use a SSV system? What must we know about the soil? A finger of sand that brings the radon to the house is one example (in my experience, three out of 50 houses exhibited this problem). Sensitivity studies are needed based on soil conditions and where the house is situated. Such a study could be very helpful to mitigators. Those in geology could supply source terms, those in soils could provide permeability factors and those in building science could supply information on leakage area locations and mechanical equipment factors which influence the pressures. There is a lot of work to be done in this area."

C(A.C.) "Considering the kind of houses, we have mostly been discussing houses with basements which represent approximately 50% of the nationwide housing stock, with 35% slab on grade and 15% crawlspace. But here in New Jersey 50% are crawlspace construction. In some states 70% are crawlspace houses, but we haven't even started on that part of the radon problem concerning dirt floor construction."

Q(K.G.) "Maintenance of fan systems would appear to be a problem since homeowners tend to ignore maintenance issues. The fans are often in difficult-to-service locations and the manufacturers cite only a three-year guaranteed lifetime. What is the cost for replacement at a homeowner's expenses -- is it several hundred dollars?"

C( ) "Although the guarantee is for three years, the service life is 20 years. The average life expectancy for this type fan is approximately 15 years."

C(K.G.) "I would question long lifetime claims when the fan is working in an environment of high moisture and problems generated by other soil ingredients".

C(D.S.) "The Canadians have experienced a five percent failure rate in 24 months on their fans."

Phase III - WORKSHOP DISCUSSIONS

MITIGATION INSTALLATION DIAGNOSTICS - M. Osborne, Chairman

C(M.O.) "This particular session starts with the premise that we have a mitigation device in place. Our emphasis will be on four different mitigation approaches and the related diagnostics. We will limit discussion to the time period when the system is being installed without a post mitigation knowledge of what radon concentration reduction has been achieved. Our question to answer is: How well is the mitigation system operating? The four areas we will be considering are: sealing, dilution by increased ventilation, basement pressurization and soil depressurization."

C(A.S.) "Regarding diagnostics and the sealing approach, caulking isn't sealing. The objective of sealing is to increase the resistance of the house structure to soil gas passage so that it is much higher than the resistance of the soil. The open area in many houses is considerable, e.g., some southern houses have leakage areas equivalent to several windows being open. In that case, the soil is the more resistant element in the flow path."

"In Canada, a program to establish the leakage area goals indicated that one square centimeter of leakage area was all that could be tolerated for the approach to work. This is a very nonlinear situation, with major improvements in soil gas flow reduction only evident when a very tight system is achieved. Epoxies often don't adhere properly. All the sealing work must be of high quality; excellent surface work must be of high quality; excellent surface preparation is key. Proper bonding to the surroundings is vital. Sealing has been tried and found difficult especially in retrofit situations. In new construction one can design a hollow where you can pour the sealant between building components. In retrofit, a jackhammer may be needed to form the hollow."

Q(M.O.) "How do you test to make sure the sealing was done properly?"

A(A.S.) "First, it is recommended that you use an experienced team that employs common sense in the sealant installation. Secondly, use sealants that are the most forgiving. We have surveyed a number of sealants, and our favorite was a solvent-hardening rubberized asphalt. The reason is that it was much more tolerant of the lack of cleanliness in the application. Other sealants required primers, but the recommended sealant formed its own primer. These sealing systems were tested in the lab using concrete blocks and then the bonds were tested for flexibility."

A(T.T.) " We ran a series of tests in the late sixty's using huge stock watering troughs, and uranium source material for the radon generation. Concrete, membranes, and paints were evaluated at Colorado State. We found extreme variation because of bond problems and seam sealing. A path of least resistance is followed by the soil gas/radon and small leaks were all that were needed for failure. Quality control was really the only diagnostic. "Holding the contractor's hand" to make certain the job was done right, according to specifications was necessary until they really understood what was required."

Q(M.O.) "What diagnostic approaches are appropriate?"

A(T.T.) "One approach is to use flux measurements to check the before and after readings. Even pinhole leaks would indicate degradation of the seal

using this approach."
A(A.S.) "These are basically water proofing materials, trowled on or poured into joints, and they work."
A(A.T.) "Bureau of Mines work on sealants should also be cited. Sealing studies by John Franklin and Bob Bates of the Spokane Bureau of Mines Office (1976-1982 literature) dealt with sealing mine walls and pinhole leaks."
C( ) "Continuous readout equipment looking for freon leakage is an example of one diagnostic approach."
C(A.S.) "Radon may be its own tracer to check for leaks."
C(M.O.) "The next topic is radon dilution by increased ventilation."
C(B.W.) "First I should state that the walk through inspection is important to check for items that are critical to any ventilation system, not just heat recover ventilators (HRV) which I will be discussing. One important point is the location of air intake and exhaust to eliminate problems of exhaust entrainment and poor ventilation effectiveness There are installation instructions available for HRVS to aid the contractor/mitigator. One caution is the case where there is a SSV system also present, the intake of the HRV must be away from the SSV radon-laden exhaust. Also, the HRV intake must not be located close to the ground, where leaves and debris can be picked up, blocking the intake and unbalancing the system."
ABOUT TEN MINUTES OF THE DISCUSSION WAS LIST HERE IN THE TAPED VERSION

C(B.W.) "....... Obviously when you do plugged flows it's nice to take your exhaust from the area of highest source strength. That can be a useful tool."
C(M.O.) "Let me open things up now in this area, and see if there are any other comments. Please try to address diagnostics."
Q(K.G.) "We've seen a lot of furnaces out there which are depressurizing basements. What effect does that have on the balance of an HRV (Heat Recovery Ventilator)? Do you check that after installation?"
A(B.W.) "We can't, because without some kind of automatic feedback mechanism you can't accomadate the needs of the other appliances. The industry response would be that they are not responsible for make-up air for the furnace; that should be provided."
C(A.C.) "But I think the important question here is not the make-up air, but rather, the effect of the circulating system, the depressurization of the basement from the pickup of return air. I've spoken with with one HVAC man who was a real authority in the field, and he said that he had seen as high as 250 cfm picked up in crawl spaces, measured in the heating system. The difference is when the fan is on and off. It doesn't have anything to do with combustion. We've seen places where we've increased tremendously the inflow through cracks by turning the furnace fan off upstairs. It's a tremendous difference, and it will affect your balance on the HRV and everything."
A(B.W.) "It will. The answer which we've given is that at least with the HRV in there, you've got a couple big holes in the wall, which help to moderate the negative pressure generated by the circulating or the combustion air, what. The negative pressure generated tends to increase the flow in the supply side, and decrease the flow in the exhaust side. It

helps, but it will tend to throw it out of balance."

Q(D.S.) "What are the duct flow measurements you talked about? Wouldn't they see that difference if there were an interaction?"

A(B.W.) "Yes, they could. That's something we haven't done."

Q(G.F.) "Bede, have you done any comparison diagnostically with respect to using a continuous working level monitor versus a continuous gas monitor? What are the differences [one gets] in the end results?"

A(B.W.) "EPA actually did some side-by-side measurements of the continuous working level and the continuous gas monitors in one of the houses where we had a heat recovery ventilator and turned it off and on. They are very comparable. But as we always saw in doing our post-mitigation diagnostics, the percentage decrease in the working levels is greater that the decrease in the radon gas."

Q( ) "I don't know how [big an] effect it would be for the small ducts, but when you're dealing with large industrial ducts, in terms of locating your traversing point, if you get it at an elbow point and count about one duct diameter down, you essentially constrain the flow very nicely. So, you can do a single plane traverse simply because you tend to get it all in one smooth flow that's due to the changing that you're doing on it. As you go across the plane, you may take more points, you don't do the normal type of traversing where you just do a 3 or 4 points; you have to do quite a few. But that does become a pretty good place to put one. And there were single plane averaging pitot tubes, the brand name used industrially was 'Anubar'that is used industrially, that you can locate some place like that without having to worry about the grid flow. These things tend to have only one grid that they use, and you may have to adjust it to a finer grid scale when you're trying to constrain it to flow around an elbow. But it can give you a good, firm fixed flow point.

C(T.M.) "I was going to mention that we're not really dealing with crawl-space houses in terms of the diagnostics dicussions we've been having. But some of the work we've done indicates that in the crawl space the communication between the duct work, particularly when it penetrates the crawl space in many places in the house, is just incredibly good. That's one of the simplest diagnostics one is going to have to do in dealing with a crawlspace house. A simple tracer-gas measurement can be used to tell what the communication between the crawlspace and the indoors is, with HVAC on and off."

Q(A.S.) "If it's good, why do you need to measure it?"

A(T.M.) "To get some indication of how good it is."

C(T.T.) "My experience in installing any kind of dilution system, heat recovery or whatever, is that there are a couple of very helpful diagnostic tools. One is the radon profile, where you have a concentration gradient and you know where you're highest areas are in the house."

C(M.O) "Let me say that most of the radon measurement things are going to be covered in the next session."

C(D.S.) "The radon profile that you're talking about is actually part of the installation. It's like your suggestion about having a radon monitor, you would then see what the best configuration is."

C(T.T.) "The second important thing in installation is that if you're able to flush the house out, and get it essentially to background, by use of a breeze-box fan or whatever, and you can determine the in-growth rate of the radon into your home, you'll find through tests and a very simple formula, that it's about 0.8 of a cfm per picoCurie liter hour in-growth into the house it takes to dilute it to background and keep the house at that concentration. There's a direct relationship between the in-growth rate of radon into the home vs how much dilution air it takes to keep that concentration."

C(M.O). "Let's move on to talk about basement pressurization."

C(I.N.) "Here we are dealing with the mitigation installation and diagnostics, and I'm assuming that everything has been diagnosed so that you have a specified, reasonable pressurization system. Let me just back up a little bit: a few things are required for a sensible pressurization system. The basement should be well separated from the upstairs. There should not be any combustion appliances in the upstairs, lest you increase the chance of backdrafting. You're more likely to be successful in pressurization if you don't have a forced-air system, although there are instances when pressurization will work even with a forced-air system. So, assuming that your house meets these conditions and you've specified a pressurization technique, let's go back now to where we are doing the mitigation installation diagnostics. The first thing to check, of course, is whether the pressure difference that you measured for the cfm with the blower-door (which Terry described previously) is in fact what you're reproducing this the actual installation. Instead of using the blower door now, the blower door fan where you continually vary the pressure and the cfm, now you have a fan with one speed or it could be a variable speed. Are you producing the pressure differences you expect with the blower-door measurements? So, you need to take a pressure-difference measurement between upstairs and downstairs, and check the flow on the fan. Then you need to go into the basement, and just as in the pre-mitigation diagnostics, check with a smoke pencil to see whether smoke is going into the cracks at that pressure difference. You have to check to see what the communication is between upstairs and downstairs. You would have specified that the major openings between upstairs and downstairs be sealed. This would alter the characteristics of the pressure difference and the airflow, so if there were large openings between upstairs and downstairs that had been sealed, then less airflow would be necessary. You could even turn the fan down to a lower speed to create the same pressure difference you were obtaining using the blower door measurements. There may be some obvious cracks or holes between the upstairs and downstairs which are still present. In all radon installations it's best to see whether there are cracks and holes in the basement, and this also might change the characteristics of the fan and the pressure difference that you measured using the blower door. The other things that you should check are the openings between the basement and the outside, for example, if there is a door that goes to the outside that is very leaky, windows which go from the basement to the outside. These should have been sealed up correctly during the installation of the pressurization system. You should go upstairs and check to see that there is no downdrafting in any combustion appliance, e.g stoves, wood stoves, fireplaces. Of course this is very difficult to do in the summer. This brings up an important point: if some of your pre-mitigation diagnostics with the blower door were done during the winter season, and the actual installation was done later on in the year, it may be difficult to find out what this system's characteristics will be in the next heating season. It may be necessary to come back during the next heating season to see whether everything is working as you thought it should. One of those things is the operation of the stoves and appliances in the upper floors. Pressurizing the basement should increase the effectiveness of the flues and combustion appliances in the basement area. There may be an unexpected interaction with the heating system. Those things also should be looked at. The location of the fan, where it is drawing air from upstairs, is very critical, and should be discussed with the homeowner. Sometimes a house may have a laundry shoot, or there may be a natural place where a fan can be placed. That might be good from the homeowner's point of view, because it is out of the way, but this may not be a good idea from the standpoint of system performance. For example,if you use a laundry shoot that goes up into the second floor, you're actually increasing the stack effect on the whole house. You may, in effect, be drawing more air from the basement to the upstairs. Try to locate the intake of the fan at a lower level. A closet also is probably not the ideal location from the standpoint of system performance, but is good from the homeowner's standpoint. Sometimes these things change when the contractor comes in and discusses these things with the homeowner.

Q(M.O.) "Could you address the question of moisture? There seems to be a potential problem of frosting and rotting out of the rim joists. [Do you know of] anything you can do to evaluate that; any diagnostic technique which you could use to see if that's going to be a problem?"

A(I.N.) "You're talking about forcing moisture out. If smoke sticks is the usual diagnostic tool to see whether there are large leaks into that rim joist area."

Q(D.S.) "Isn't that part of post-mitigation, because you're looking for some actual effects that might start to show up?

A(M.O.) "Maybe not. If at the time you're doing this there is something you could do to find out whether there is a significant leakage, or whether there is a moisture problem."

C(D.S.) "Along these lines, if it's the pressurization, what is the flow rate, just what are we actually moving out? You could do a calculation to find that out if you knew the exit rate of the air, the moisture content -- maybe moisture content is an important variable, and should be covered in pre-mitigation."

C(B.T.) "I have several comments to make. One is on the moisture. First of all, in the homes in Spokane WA, we have not observed a change in the whole-house ventilation rate after we've done this. We've increased the basement ventilation rate considerably, in some cases we've doubled or tripled it. The air has to leave the house somehow, and under natural conditions it leaves the house near the top. In the climates typically found in the U.S., we haven't had problems with rotting around the exit points. We might expect to see moisture from condensation collecting and causing rotting in structural members in the basement. But I don't know whether it would be any worse than seeing it at the top of the structure under natural exfiltrating conditions."

C(T.B.) "We have seen that frequently, under natural conditions."
C(D.Sa.) "I don't think that is necessarily true, because you're looking for a condensing surface, a cold surface against which this warm air will be pushed. Up in the attic, there is no condensing surface; there you've got the attic ceiling and then the insulation sitting on top of that. There is no surface on top of that; there's a big space up there."
C(A.S.) "But the insulation is one condensing surface."
C(D.Sa.) "Yes, but it's not like having a cold wall there with insulation, so that the air passes through the insulation and then hits a cold surface."
C(T.B.) "The condensation happens right on the underside of the roof sheathing. I've seen plenty of moisture damage in attics."
C(D.H.) "We agree with Terry and have published a number of reports on attic (and crawlspace) moisture problems.
D(D.Sa.) "But at least attics are ventilated, whereas the wall is not ventilated, so I think there's a bigger potential."
C(B.T.) "It might happen, but I think that [should be] a follow-up measurement to this. We've been doing this only nine months, so we really haven't been through it."
C( ) "Someone brought up an important point. If you could, with a smoke pencil or other means, identify the large leakage paths existing in the house, and plug the big holes, that might be of some value. As we know from the moisture-damaged houses of the far north, the big problems happen when there's a big leakage path. The other thing is that in the houses that you've done, you're not going to see rot yet, because it takes a long time to get to that. That's not to say that it won't happen."
Q(R.Si.) "I was wondering whether anyone had measured a bona fide change in moisture before and after pressurization."
C(T.B.) "We've changed the whole humidity dynamic. A great deal of the moisture in that building is probably entering with that soil gas. Now that we've prevented that, we may have cut the moisture source strength by a factor of two. We have countervaling physical principles going on here, with no way of knowing whether we'll have a problem."
C( ) "We have measured relative humidity in upper floors and basements and overpressures and we've seen declines almost universally in basement humidity."
C(B.T.) "I have a few other comments, and the first one applies not only to heat exchangers but also to basement pressurization. You have to decide what overpressures you're going to operate at, and what are acceptable overpressures, and what are the maximum flow rates that you can live with when you actually set up your blower-door. Is 300 cfm too much, or 400 cfm? For economics, we use something like 300 or 400 cfm as an upper bound. With anything more than that you'll have a lot of drafts, and you also pay an energy penalty to move this large volume of air. Another question concerns the pressure: what pressure do you have to develop in the basement to override 90% of the conditions. We're using something like 3 pascals overpressure (difference between basement air and outside air), but that may not be enough, and that may be suitable only in certain climates. As you go further north, you may have to go even higher, to override more extreme conditions."
C(K.G.) "We have a couple diagnostic questions. Being from the energy

field, we worry about home-owner comfort, and I think the location of the fan intake is important. As Brad mentions, should we check for a local drafty situation? Also, regarding the HVAC operation, most of our newer homes have central air conditioning, so it would be a problem all year round, not just during the heating season. Should we check the HVAC operation and its effect on the pressurization system?"

C(T.B.) "That goes right along with my diagnostics question. What happens to the pressure field when you turn on the furnace? And what happens if you turn on the 'Jenaire' all of a sudden you're exhausting 400 or 500 cubic feet per minute from the upstairs chamber in competition with the fan that's blowing air down into the basement? The question is, how do we test for the impact of other exhaust devices on our pressurization system? I suppose that the answer is to turn them all on at once and see."

C(M.O.) "I'm sorry, but our time is up on this topic. Now we need to move on to soil depressurization."

C(B.T.) "We talked about this a bit already yesterday. The most important things to check are: how extensive a pressure field have you developed in the soil? Is that strong enough to resist the competing pressures from wintertime stack effect and from exhaust appliances? Also, do you have some sort of 're-entrainment' That is, is the fan you're using somehow mining high concentrations of soil gas and blowing it into the house, or is it coming back in from from outside? Those are the three things you want to test for, and I do that typically by using smoke sticks. If I were stranded in an abandoned radon house, and could select only one thing to have with me, it would be smoke sticks (not Bayer Asperin) and a respirator. Magnehelics and incline manometers both have problems at the low end range. You can tap Magnehelics and the needle will move and stay stuck in a different spot. Incline manometers mean that everything you own has red gauge oil on it. And they are slow to move if you're moving any air column, you really have to wait for them to stabilize. Although they are expensive, the electronic sensors maintain calibration very well, and respond instantaneously. I think they are worth the money.

You can check with all those things. You can turn on all the exhaust devices in the house, or artificially induce with a fan a wintertime-type negative pressure, to see if you can overwhelm it the mitigation system, and have soil gas entering where it used to be leaving, with your soil depressurized."

C(D.S.) "if you have the design pressure in the weakest part of your system, then it is not going to be overcome by any wintertime design conditions. For re-entrainment I check with the freon tracer. Two important things to remember are that 1) silicone will give you a false positive; it will beep like crazy at silicone, and 2) if freon comes into contact with an open flame, phosgene is formed, which is not very nice stuff."

Q(M.O) "Is there further diagnostic imput?"

A(D.Sa.) "I'd like to say something about radon mapping. We find that you don't want to fix something which is not broken. If you have multiple slabs, crawl spaces, holes, etc. you can go in there and make sniffer measurements and decide where to mitigate and where not to mitigate."

C(I.N.) "We were talking about the dangers of tracer gasses. We should be glad that freon is not among those which react with ozone."

C(T.B.) "It depends on the one which you are using. Probably R11 and R12 will soon be banned. You can either use an R22, which is more acceptable, ... the ozone is a serious issue for me, and I don't lightly dump lots of freon into the atmosphere."

C(L.K.) "Along the lines of what Terry was just saying about setting a match to silicone, I think people should be cautious about the sealant they use; make sure that it is appropriate for internal use. In my region the Center for Disease Control is looking into a log cabin, where someone used caulking on the inside of the house that was meant for external use only. The caulking may have caused a child to be born with leukemia."

C(D.S.) "It has been stressed quality assurance and quality control is important in the installation phase. It seems to me that many leaks could be avoided by making sure that it's done right to begin with. It seems to me that that should be one of the diagnostics in the installation. I'd like to ask the mitigators how often they've had to go back and fix things that weren't done right along those lines."

A(D.Sa.) "Do fifty percent of the systems have some sort of leaks?"

C( ) "I think that's too high -- maybe 25%".

C(M.Me) "Our standard procedure is to check out the system with freon when it's installed. We do double-check sometimes; for instance, when we have an installer putting in the system, the installer is supposed to check out the system with freon before leaving the site, and we generally return within 48 or 72 hours and do an independent quality control check. We've found leaks using freon in the air perhaps 10% of the time. These leaks occur in two places: one is at the joint where the fan is coupled to the pipe going outside, and the second one is at the band joists where the pipe is exiting the house. That we find is frequently a difficult installation point, because you're working with bends in the pipe in constricted space, often between floor joists). It's the point where the utmost care has to be taken"

C(A.S.) "I would comment that I really admire people who have the courage to install fan systems with the portions internal that are under pressure. I've never had enough courage for that and we've always mounted the fan outside."

C(M.Me) "We're losing our courage.(laughter) The pictures we showed yesterday had that roof-mounted fan for that reason. The problem is that in terms of the installation costs, it's considerably more expensive, and so we're generally offering people three alternatives: we say it's cheapest and simplest to out through the side of the house, but here there are the most serious concerns about venting. The second best is to go up through the roof with the fan mounted in non-living space, an attic or crawl space. Preferable is to get the fan ouside the house, mounted on the roof. Each step buys you an additional level of protection, at an additional cost."

C(M.M.) "I'm not entirely sure whether ... although obviously it must be smaller, we've seen no evidence in our installations where all our fans are ground-mounted, that this prevents you from achieving 4 pCi/L per liter or less, on average."

C(M.M.) "With ground-mounted [fans], our concern is with human traffic. Most of our clients, in fact, have small children. That seems to be a driving force in installing mitigation systems in that 5 to 40 pCi/L range."

C(M.O.) "We have time for just a few more questions."

C(RSi) "I have a comment on the problems with the side mounts. We've found a lot of re-entrainment six or eight feet away around the collar joists, or band joists, or the plate foundation interface area. So, we've elected, if at all possible, not to give the home-owner an option. We price the job going through the roof system."

C(A.C.) "The new manual will show that as the only option."

C(R.Si) "Also, as was mentioned earlier, the problem going along with that is inadvertant exposure of kids, even if there are plants or if the area is protected. That's not a long-term protection mechanism. The [plants] could be removed, and the area could then be used as a play area."

C(D.S.) "Just one more point, along the lines of the this quality assurance, quality control. Someone mentioned double-checking: that should be routine. And there should be a checklist. A lot of this seems to depend on the experts: 'well, I know what should be done'. But there's no record of what was done, and there should be a checklist as a diagnostic that should be followed."

C(T.B.) "Actually, Bill Brodhead made a checklist for the ORP course for each of these mitigation techniques. There's at least something written down on paper."

C(D.S.) "A course is one thing, and practice is something else."

Q(T.B.) "Bill, do you actually use your checklist?" (laughter)

Q(L.H.) "I have another quick question for the mitigators. Are subslab ventilation and dampers installed routinely in the system to balance the flow during the installation?"

A(R.Si) "It's routine for us. We install damper systems to balance the depressurized area, depending on what we're dealing with. It could depend on whether it's going into an adjoining slab, or an area that doesn't have the same type of pourous fill as another area, or possibly the specific area that it's dealing with, so that we can adjust and have relatively uniform flow throughout the system."

Q(L.H.) "Do you do that on the day of installation?"

C(M.O.) "Right."

C(M.O.) "Do you have a rule of thumb on dampers, as far as how many you would have in a system?"

C(R.Si) "No, it's pretty specific as to what we're dealing with at the time. We install dampers in every lateral."

C(M.O.) "OK, that's what I was [asking about]."

C(R.Si.) "The other thing is that if it's a direct line down from a fan, in my experience, we'd have more direct draw from the straightest run of pipe, and we want to be able to divert that through areas."

C(M.O.) "Our time is up, that ends the Phase III Diagnostics Section."

PHASE IV. WORKSHOP DISCUSSIONS

POST MITIGATION DIAGNOSTICS - Bruce Henschel, Chairman

C(B.H.) Four basic diagnostic issues will be discussed here. First, what is the universe of diagnostic techniques that might be considered under post-mitigation diagnostics? Second, is each technique practical and cost effective for a commercial mitigator to use? Third, our emphasis will cover the confidence we have in the technique, the experience to date, the improvements needed, and the interpretation of the results. Fourth, who should use the technique? The commercial mitigator, the homeowner (long term items), or the research community? What kind of diagnostics should be used if the system is working, but not achieving the 4 pCi/L guideline value is an interesting question but should be referred back to the earlier diagnostic categories.

"In order to conserve our discussion time I will start the informal talk on the list of diagnostic techniques for post mitigation. What are the universe of techniques that fall into this category of diagnostics? The obvious techniques include measurement of Rn and/or Rn progeny. Should we measure Rn gas or Rn progeny or both? Where should we make the measurements -- in the living space, or the basement; or from a research standpoint, in walls or under the slab? What is the timing and duration of these measurements (i.e., short term, long term measurements)? What levels are we looking for -- does every measurement have to be less than 4 pCi/L?

"Another diagnostic technique is evaluating the effect of weather and events such as appliance use on the radon inflow.

"A third diagnostic item is evaluation of mitigation system fan size.

"A fourth item is the evaluation of back drafting of combustion appliances with the mitigation system operating and depressurizing part of the house.

"A fifth diagnostic item is visual inspection, seal functioning over time. Moisture problems such as band joist rot due to moisture extracted by the mitigation system, etc. and a sixth, the effect of SSV on the soil around the foundation -- possible freezing problems, drying out the soil, etc.

"Finally, as a general category, other side effects such as ill effects from the caulking, etc."

Q(D.S.) "This list has many items the commercial sector may not be interested in. Who has the long term responsibility for the system operation and side effects?"

A(B.H.) "I am assuming that the homeowner may have to take the responsibility for the long term items. In addition, researchers may have similar interests for the long term. The techniques listed that should have the most interest to commercial mitigators are measurements of radon and radon progeny, and assessment of weather, appliances, and back drafting. Their interest in optimal fan sizing may prove to be a question mark."

Q(A.C.) "What part of the post-mitigation diagnostics is the commercial mitigators responsibility, and what part is somebody elses? David Saum, what do you guarantee as far as reduction of radon below a certain level?"

A(D.Sa.) " My guarantee is for a year, nominally. Long term testing is an interesting area, but we have had trouble finding a group who routinely handles the long term. We provide charcoal cannisters and alpha track measurement devices for the intermediate term."

C(A.C.) "Part of the EPA demonstration program will be to continue yearly testing for at least five years on all of the houses that were mitigated in the studies. We will perform a three-month alpha track survey during the winter season. In the New York study we are going back to resurvey what they did four years ago to see how well the mitigation has held up and to determine if there are any problems."

C(T.B.) "When it comes to problems, the homeowners determine who they will turn to for assistance. Sunday morning calls are a real problem for the mitigator."

A(A.C.) "In most states the mitigator doesn't have any responsibility beyond one year."

C(T.B.) "Unfortunately most homeowners do not believe that. I have calls on houses I built five years ago, but now the homeowner has installed a dimmer switch that bothers his radio and its my fault. The homeowner will hold the person that did the work responsible as long as possible."

A(M.Me.) "Let me quickly explain which tests we do and why. Once our system has gone through our quality control check, we supply the homeowner with charcoal canisters which they place in the house for checking performance over the intermediate term. Once we get back an indication that radon levels are below 4 pCi/L, then we install alpha track for a three-month evaluation. Since we are often heading into spring-summer, we ask the homeowner to wait until the next winter to make this three-month test. We have discussed radon progeny measurements but since we don't have the before measurement of radon progeny, an extensive set of after measurements creates a new set of problems for ourselves. The before diagnostics limit what post diagnostics are appropriate. The post set of measurements are limited to radon, not pressures, etc. We are 'listening for side effects', but that is the extent of it."

C( ) "In the case of 12 mitigation companies in New Jersey, the testing is far more limited than that described here. Very few are doing much in the the way of diagnostics. It is very simple out there, let's get in, put something in place, let the homeowner see what the results are. No one is doing work adjusting dampers, two are doing freon post-tests. There isn't a lot of diagnostics going on out there."

C(T.B.) "Chick and I surveyed a number of installations in New Jersey. About half the systems weren't working properly but could have been if simple post-mitigation diagnostics had been used, such as checking the effect of the suction away from the suction hole."

C( ) "Even the simple post-mitigation measurement of radon concentration has been left up to the homeowner. One example of really simple diagnostics used by a company who has installed 400 SSV systems is to put two five-gallon buckets of water down the 4-inch diameter suction hole. If it moves quickly into the soil this means good communication and they proceed. If the water isn't quickly drained they move out to the edge near the footer and drill additional suction holes counting on the soil to have fallen away from the footer and thus providing good perimeter communication. They might also move to trenching. What ever is done on radon or radon progeny is the responsibility of the homeowner."

C(R.Si) "Check lists are important for each specific system."

C(R.S.) "A competent diagnostician should be checking that the whole house works successfully, e.g., interaction between the mitigation systems and appliances, etc. There is a moral responsibility for following up the higher radon houses, say greater than 50 pCi/L. Both the research community and government officials must make the commitment to provide the kind of understanding necessary through a long-term radon measurement program to evaluate these mechanical mitigation systems over the long term."

C(T.T.) "I like radon measurements for post-mitigation diagnostics. If you kill the parent you don't have to put up with the children. We don't need to measure working levels; we have never accounted for the unattached fraction of daughter products. I use a grab sample profile of radon and compare it to the pre-mitigation data. I have had 100% success in predicting whether the home will exceed the annual radon average based on radon data (employed on 80% of a 600 home sample, involved with mine tailings). I also look for hot spots in the radon profile survey."

Q(D.S.) "Are you looking at an annual performance? That is where the 4 pCi/L came from?"

A.(T.T.) "I am comparing to a year-long Ripsu sampling."

C(D.S.) "We are talking about annual average and not a grab sample and then you are done."

C(T.T.) "I thought we were talking about several phases of post mitigation. I am suggesting a method to let you know where you are."

C(R.S.) "A grab sample isn't the whole story. One must consider longer term measurements such as alpha trak in several locations as a minimum."

C(M.C.) "New Jersey has requested each mitigator to supply before-and-after measurements to show what has been achieved. These are mostly carbon canister measurements of radon and not longer-term measurements."

C(T.B.) "We have a serious problem in the private sector with conflict of interest. If I were doing commercial mitigation work I would make sure the pre-mitigation reading was high and all post-mitigation reading would be low. The potential for fraud is extremely high after selling thousands of dollars of mitigation. We need independent radon testing because there is the whole question of liability if you take your own measurements."

Q(T.T.) "What is an annual average? What does it mean when we obtain it? Is it reproducible the next year?"

A( ) "No, there is no such thing as an annual average is the answer."

Q(I.N.) "Since there are a number of EPA people here, in subsequent revisions of protocols is EPA going to reconcile .02WL and 4 pCi/L? EPA should resolve the question. In some areas it pays to measure radon progeny because of the equilibrium fraction is less than 50%. EPA should settle on either radon or radon progeny. These questions are becoming central to real estate transactions."

A( ) "The guideline is written in terms of 4 pCi/L for indoor radon, the type we are discussing."

A(A.C.) "No, in every case it's given both ways."

A(W.L.) "The conception in the research community considers the ultimate dose to the lungs and risk. Because of compensating factors the dose models indicate that radon gas measurement is probably better as an approximation to dose than radon progeny in contrast to what we thought a few years ago. In a sense there is a very strong movement toward radon measurement and

guides because of its practicality but also because it makes more sense from ultimate risk."
A(A.C.) "From the EPA demonstration programs, the decision making is based on radon, continuous monitoring or canisters."
C(B.H.) "The measurement of radon and ventilation effects is a critical area for continued research. What happens to WL and unattached fraction are closely related to ventilation taking place in the space."
Q( ) "Don't we know what is the unattached fraction? The health community is saying probably the unattached fraction makes up for the difference in ratio and consequently either one gives you essentially the same thing. What happens to the unattached fraction depends on the system -- is there a filter present -- these points need to be looked into."
C(R.S.) "We can't rely on WL measurements to have any assurance that you have made any improvement in the radon situation."
Q(A.C.) "Are any real estate companies requiring WL measurement?"
A( ) "Yes, in Pennsylvania. A real estate relocation company is using WL measurements with continuous monitoring over one day. This is one of the two largest relocation real estate firms in the country, Home Equity Relocation."
Q( ) "What instrument are they using?"
C( ) "That depends on the contractor, they don't do their own testing." (Some discussion on the size of the real estate market handled by such firms.)
C(B.H.) "Summarizing, radon is easier to measure and may be a better indicator given that you have to make a fairly simple measurement -- you can't be measuring WL as a function of particle size in every house the commercial mitigator goes into."
Q(T.B.) "I have almost given up on summertime measurements because of the seasonal variability. Who is going to do long term monitoring in buildings? I don't think it is the mitigator's job."
Q( ) "That is an important issue and gets back to the question of isn't it the homeowner's responsibility to measure his house over the longer term?"
A(T.B) "The mitigator leaving canisters for follow up measurements was one idea advanced. A commercial house offering that service is also very interesting. New Jersey's follow up program is another example of longer term testing."
A(A.C.) "Your getting back to the question of "is it a legal responsibility? EPA's program is a voluntary program and always will be because we don't have the legislative mandate to set a regulation. Some states are setting regulations. There will not, as far as we know, ever be a Federal regulation."
C(J.H.) "New Jersey has done 1400 confirmatory tests and 200 post remedial tests. One major problem is that the homeowner doesn't want the government to know the level of radon in their house. They don't trust the government unless they need some financial support. Interesting findings from the post remedial tests; about 47% used sealing, 18% used HRV's, 22% used SSV, the rest used other ventilation systems or methods. Thirty-nine percent did the remediation themselves even though the homeowners were well-off financially. These owners are concerned with cost. Before mitigation 97% were above 4 pCi/L, while after mitigation 48% were above 4 pCi/L."

C(A.C.) "About half made it to the guideline."

C(J.H.) "The before levels were between 3 and 400 pCi/L."

C(A.C.) "The goal of the mitigator in any home is not for a given percent reduction, but is to get the post-reading as low as possible, and at least below 4 pCi/L."

Q(D.S.) "Cost effectiveness was cited as one of the issues. You must put mitigation on an objective basis. We really haven't done that in the U.S. Sweden is doing that. Are there any ideas at this point of how to pursue that goal?"

C(A.T.) "In some places dehydration will occur to depths of several meters. It could significantly increase radon transport."

Q(B.T) "Why wouldn't it decrease the source strength because of emination fraction?"

A(A.T.) "You are talking about moisture changes of a few percent while I am talking about changes from 60% to 30%."

C(T.B.) "You get condensation on top of the SSV pipe. If you've done the installation correctly the moisture runs back into the soil, otherwise it interferes with the fan and you'll hve to fix it."

C(A.T.) "I don't know if it is a real effect, all I know is if it does dehydrate the sail it will have an influence on the source term."

C(A.C.) "Larry Kaplan reported that in one installation he was monitoring the SSV system produced 2 1/2 gallons of condensate per day."

Q(T.B.) "Was it running back into the soil?"

A(A.C.) "He was draining it away, but I don't know exactly how he was doing it."

C(B.H.) "In terms of the diagnostics we would use to evaluate this, it might be in the realm of the developers and the researchers either measuring changes in the source term, or the moisture content of the soil or something to that effect over the course of the project."

C(A.T.) "If you're doing periodic monitoring over years, and finding the radon levels are rising and the mechanical mitigation system is working, this could be the reason for the source terms changes.

C( ) "I think the opposite situation takes place. As the soil drys out the suction system becomes more effective and reaches out further and the performance gets better."

C(A.T.) "I claim some knowledge only of the source term."

C(A.C.) "As long as you have a negative pressure difference across floor and wall cracks it probably doesn't really matter how dry you get the soil. Even if the source strength increases it doesn't mean more radon will enter the house."

C(A.T.) "That's a good pointp; the key is that the gradient is toward the soil."

Q(B.H.) "Our time is running out and I would like to turn the discussion back to radon monitoring, something near and dear to everyone. The question is where do we monitor? For those that are doing monitoring as part of commercial installations where do you monitor - upstairs, basement, both places?"

A(T.T.) "Usually we monitor 6 to 8 places in the house. I think many people are overlooking that radon levels can increase in living spaces while being reduced in the lower house locations. I believe a profile of radon levels is necessary, not just basement measurements."

A(D.Sa.) "We try to make radon measurements in a couple of places that were measured before, often on each floor."

A(M.Me.) "Always a minimum of two charcoal canisters are used, plus one alpha track which the homeowner decides on the placement."

A(I.N.) "We try to follow the EPA protocalls."

C( ) "Oh my God, I'm sorry for you."

Q( ) "Which one?"

C(I.N.) "It is rather difficult. There are two types of measurements the EPA suggests. One is the screening measurement which is done at the lowest level of the house. The other is the so-called follow up measurements which in the present protocol is the pre-mitigation follow up. So you would try to duplicate those location measurements in the post-mitigation measurements with the charcoal canisters. The measurement of radon or radon progeny is still a question."

C( ) "One of the problems that drives the pre- and post-mitigation measurements is the time delay that is necessary to purge the lucas cell after measuring a hot spot. There is a definite research need to develop a rapid radon measurement system which doesn't have the problem measuring the radon daughters. That development would change the whole complextion of what pre- and post-mitigation measurements would be made."

C(A.S.) "Eberline appearently has been working on an electrostatic cell that removes the daughters and measures radon."

C(A.T.) "Paul Tease claims a patent on that."

C(D.Sa) "Sniffing measurements limited to only a few minutes has allowed us to quickly clear the cell even when covering ranges from 10 to a 1000 pCi/L. We also seem to see significant reductions under the slab. You don't agree?"

C( ) "The holes drilled into slab and walls for diagnostics have been plugged with putty or tape until after the system is installed. The principal measurements have been pressure but where we have interesting houses we have gone back, time permitting, and we sniff there on how quickly radon levels drop and how far.

Q(A.C.) "What is the highest levels you've measured after several months?"

A(A.S.) "50,000 pCi/L near the beginning of monitoring in the spring, and 35,000 the following fall out of the subslab."

C(A.C.) "We have seen some very high levels even after long periods of time."

C(B.W.) "I would like to tell the story of a building contractor in Pennsylvania who filled out a form to his insurance company that he was now going to install radon mitigation systems. The next day he received notice his insurance was cancelled. We are in the business of installing ventilation systems is the response to that issue."

C(W.L.) "I want to go back to the issue of long term effectiveness of mitigation. It is clear there is not going to be federal regulation on this issue in the near future. States are taking some actions; some will take different actions and that may not be a very satisfactory situation. That raises the question of whether the industry could develop a voluntary standard, especially the cream of the crop which is here."

A(B.T.) "The ASTM task group is attempting to look at a standard for long term measurements.

C(A.C.) "They will never get 50% of the mitigators to belong."

C( ) "But that's better than 10%."

C( ) "But it's possible that the EPA could come out with a recommendation that the states could put into their regulations for long term measurements."

C(D.S.) "EPA began to get involved with ASTM 1 1/2 years ago in that same subcommittee. I haven't heard of any change in that policy to work through ASTM to set up such guidelines."

C(A.C.) "Eighty percent of the mitigators have never heard of ASTM."

C(D.Sa.) "If we had the guideline in hand, it might take three years to move to approval. The process is very slow."

C( ) "A group of leading mitigators is one idea that has been discussed as a voluntary type of control. Dissemenation and gathering of information as well as a form of regulating body that would overse the type of mitigation installations and establish minimum standards. We are looking for volunteers."

C(T.M.) "Such an organization would help to upgrade the image of this new industry as well as raise the prestige of mitigators who subscribe to the guidelines."

SUPPLEMENTAL RADON DIAGNOSTICS INFORMATION

FROM THE PIEDMONT STUDY

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The Piedmont Study refers to the detailed radon mitigation and diagnostic study conducted in 14 homes in the New Jersey Piedmont area from 9/86 to 9/87. Seven homes were investigated by Lawrence Berkeley Laboratory and a second set of seven homes were studied by Oak Ridge National Labs and Princeton University. This data-intensive, instrumented study was cooperatively funded by the U.S. Environmental Protection Agency, the U.S. Department of Energy, and the New Jersey Department of Environmental Protection.

Instrumented measurements included: (1) basement and upstairs radon; (2) differential pressures across the basement/subslab, basement/upstairs and basement/outdoor interfaces; (3) temperatures at basement, upstairs and outdoor locations; and (4) central air handler usage. A weather station was located at house #5, monitoring: (1) wind speed and direction, (2) barometric pressure, (3) precipitation, (4) soil temperature, and (5) outdoor temperature and relative humidity. A time-averaged value of all of the above parameters was recorded every 30 min. Several additional parameters were monitored on an intermittent basis in all or selected homes. These included multizone air infiltration rates which have been measured in all homes using passive perfluorocarbon tracers (PFT), and in one home using a constant concentration tracer gas system (CCTG).

The purpose of the analysis of the continuous time series data set available from the Piedmont Study is to provide insight into both the usefulness and accuracy of some of the diagnostic measurements made by practitioners as well as insight on the interaction of various measured parameters with the time-varying radon concentration. The analysis presented here was performed at Princeton University using the data from the seven Princeton/ORNL research homes. These homes were chosen to be of similar basement types, and Table 1 compares substructure specifics and other house parameters.

Table 1. Summary of house parameters.

House No.	Sub-Structure	Modifiers	HVAC	Radon[b] (pCi/L)	ACH (h^{-1})[c] -50 Pa.	Soil Perm.
I	Basement W/Slab, Att. Gar. W/Slab	Float. Slab, Sump	Cent. F.A., Gas	B:73 U:16	16.2	Mod.
II	Basement, Att. Gar. W/Slab	Sump	Cent. F.A., Gas, W/AC	B:24 U:16 A:15	12.3	Mod.
III[a]	Basement, Att. Gar. W./Slab	Float. Slab, Sump	Cent. F.A., Oil	B:156 U:49 A:60	11.9	Mod.
IV	Basement W/Slab, Att. Gar. W/Slab	2 Sumps	Cent. F.A., Oil W/AC, Auto Setback	B:103 B:128 U:31	9.9	Very
V	Basement, Att. Gar. W/Slab	Float. Slab,	Cent. F.A., Elec. Ht Pump, Auto Setback	B:60 U:25 U:36	8.2	High
VI	Basement W/Crawl Att. Gar. W/Slab	2 Ht Exc. Sump	Cent. F.A., Oil, W/AC, Auto Setback	W Ht Exc B:25, U:14 W/O Ht Exc B:30-35	19.8	High
VII	Basement W/Crawl Att. Gar. W/Slab	Float. Slab, Sump (Part. Seal)	Cent. F.A., Gas, W/AC,	B:36	11.0	Very Low

[a] control house

[b] B - basement or crawlspace, U - 1st floor above grade, A - 2nd floor above grade

[c] depressurization only, basement door closed, blower door on main entrance, Nov., 1986 measurements.

One question which is often asked by both researchers and practitioners regards the difference in accuracy in a two day versus a four day measurement of the average radon concentration. How much better is a four day average over a two day average? Without addressing the question of the accuracy of the measurement device itself, we have used the Piedmont data on continuous radon measurements to determine how variable the two day versus four day averages are over different seasons.

Figure 1 plots the differences between nested two day and four day averages for the control house over 200 days of the study. Each point is the difference between the average radon level over a two day period and the average over the four days centered about the two day span. The average difference is zero if a long enough time span is considered, but any given difference can be either positive or negative, with an alternation in sign being the norm. The standard deviations noted on the figure are those associated with the DIFFERENCES, not the radon levels over the period. For the winter, the deviation of 1.40 pCi/L is 6.4% of the radon level. This represents the scatter attributable to your choice of two versus four day sample intervals.

Figure 2 is the scatter plot of the two day averages versus the associated four day averages. The differences between the averages account for the deviation of the points from the straight line. The standard deviations given are those of the daily radon levels over each season. Different symbols are used for each season to show how the radon levels changed over the long term.

Figure 3 shows a four day span of basement radon levels in two homes during a period of no rainfall. Although one of the radon curves has a very dynamic character and the other is somewhat static, the differences between the 2 and 4 day averages for BOTH curves is negligible.

Figure 4 shows a basement radon level reacting strongly to rainfall. The spike produced by rainfall dominates the curve, and the choice of either a 2, 3 or 4 day sample interval makes about a 10% difference in the actual average radon level for this house during one rainstorm. This 10% figure is comparable or less then the statistical variations commonly found in the readings of passive sampling devices placed side by side, however it could become significant as the error in the passive sampling devices improves. The behavior of House 7 during rainfall, displayed in Figure 4, had the largest response to rain out of the seven Princeton/ORNL homes.

The top box in Figure 5 shows the variation in the basement and upstairs daily radon concentration during one week in February. The Julian date is shown at the bottom. The basement radon concentration has a distinct diurnal periodicity with the daily minimum varying from the maximum by a factor of between 1.5 and 2. Use of the heating system appears to be part of this diurnal cycle. The heating system consists of an oil combustion unit with a heat pump, located in the basement, with a forced air distribution system throughout the house. During the sleeping hours the system is manually shut off, and the basement radon slowly builds up. When the homeowner rises between 7 and 8 a.m. the oil combustion unit is manually turned on and left on until the upstairs temperature reaches approximately 70 F. The system is then manually switched over to the heat pump, which continues running automatically on a thermostat throughout the day. If the outside temperature drops below 30 F during that time, the system automatically switches over to the oil burner again. Before retiring at night, the homeowner again manually turns off the entire heating system. The second box in Figure 5 shows the basement infiltration (in air changes per hour, ACH) averaged over hourly time periods using the constant concentration tracer gas system (CCTG). The third box plots the difference between the upstairs minus the outdoors temperature (top curve), and the percent time in each 30 minute time period that air is flowing through the air handler (bottom curve, with units given on the right ordinate). This measurement does not distinguish between oil combustion and heat pump use. The bottom graph plots the outdoor minus basement and subslab minus basement pressure differences in Pascals. The more positive this difference is, the greater the depressurization of the basement relative to the subslab or outdoors.

These graphs tell the following story. The basement radon builds up during the night, when there is no heater operation. Once the heater comes on the basement air gets mixed with the upstairs air, and a slight buildup in the upstairs radon concentration can be seen to occur during the period when the basement radon is decreasing (top graph). The basement is depressurized relative to the outdoors, subslab, (bottom graph) and upstairs (not shown) during the cold winter days plotted here. Deviations from this baseline occur in the initial combustion stage of the heater use. (Note: the overall increased outdoor - basement pressure difference over the period between days 54.5 to 56.0 corresponds to a strong and steady wind from the northwest. This correlated behavior also shows up in other time periods.)

Three processes can occur during heater use which affect the basement radon concentration. 1) The basement air becomes mixed with the upstairs air, which dilutes the radon. 2) The increased depressurization of the basement can increase the amount of soil gas, and thus radon, flowing into the basement, increasing the indoor radon concentration. 3) The increased depressurization of the basement can increase the amount of outdoor air flowing into the basement, diluting the indoor radon concentration. The difference in the leakiness between the substructure and soil gas compared to that of the substructure and the outdoors determines whether process 2 or 3 above will dominate, and thus whether the basement radon concentration will be enhanced or diminished. Along with the increased basement depressurization during the initial combustion stage of heater use, the second graph shows an increase in the basement infiltration of about a factor of 1.5 to 2.0. The basement infiltration is the sum of the infiltration from the outdoors plus the infiltration from the soil gas. There is a way to make the second of these terms go to zero, and thus obtain the relative magnitudes of each of these two terms in the unperturbed case. The perturbation which can be applied is a subslab ventilation system.

With a subslab ventilation (SSV) system operating and effectively reducing the indoor radon levels to below 4 pCi/L, the basement infiltration from the soil gas is negligible. The total basement infiltration would then consist only of the contribution from the outdoors to the basement. It is possible that the SSV system can cause increased air to flow from the basement either out through porous hollow block walls or by some other mechanism out of the basement into the subslab and out the SSV system. Consequently, this could increase the basement infiltration from the outdoors. Comparing the basement infiltration with and without SSV in use will still give information on the difference between the infiltration from the soil gas versus the outdoor air, since any increase in outdoor to basement infiltration due to the SSV operation would be more of a constant source rather than sharp changes as observed when the combustion heater comes on. Also, initial analysis does not show any significant shift in the baseline for the basement infiltration when compared to conditions without the SSV system operating.

Figure 6 is a plot of the same parameters as in Figure 5, for four days when the SSV system was operating, subsequent to the days plotted in Figure 5. The radon concentrations dropped to well below 4 pCi/L, indicating the SSV system was effective. (Any measurement of radon below 1 pCi/L is within the error limits of the detector). The bottom graph shows that the subslab air is depressurized relative to the basement air by about 13 Pa, due to operation of the SSV system. The large increase in the basement infiltration at day 59.6 is due to the homeowner airing the basement. The average basement infiltration during the initial use of the oil combustion system each day is 0.33 ACH for days 50-58 (Figure 5) and 0.28 for days 58-62 (Figure 6). The difference between these numbers suggests approximately 0.05 ACH infiltrates the basement from the soil gas during the combustion phase of heater use, when the SSV system is not operating. Although this analysis is preliminary and trends are suggested, future more controlled experiments are needed.

No significant change in the baseline for the basement infiltration is observed in this preliminary analysis, any overall decrease due to stopping infiltration from the soil gas may have been compensated by increased infiltration from outdoor air due to any air flow from the basement during SSV system operation. Leaving that for future more detailed analysis, the data here suggest that in house 5 (the tightest house in the 7 study homes) between 1/6 and 1/4 of the total infiltration into the basement is from the soil gas when the SSV system is not in operation.

Figure 6a shows the radon concentration in the basement, in one location of the inner hollow block wall, and in the subslab gas under the center of the slab during February 20 through March 2 (Julian day 51-61, as shown in Figures 5 and 6). It is interesting how much higher the wall concentration is than the subslab concentration; which was consistent over time in these two specific locations. We did not find any other wall location in this house which gave readings this high. The wall faces east and is not adjacent to a slab on grade. (Note that hollow block walls between a basement and a slab are often the hottest wall in a given structure, due to the slab trapping soil gas.) The wall radon shows some of the daily periodicity displayed by the basement radon concentration and, to a lesser extent, so does the subslab radon concentration. The wall has better air flow communication than the subslab with the basement air due to the very porous nature of the cinder (or concrete) hollow block walls. This points out the role of porous walls in soil gas entry.

The perimeter drain seal shown in the insert in Figure 6a is an effective way to close perimeter drains, while still allowing the SSV system to communicate with the air in the hollow walls. This is demonstrated on February 26th when the SSV system is turned on and all the radon concentrations drastically drop. In particular it is interesting how the wall radon level actually drops lower then the subslab level implying more effective ventilation of the walls than the center of the subslab area. The two SSV penetrations into the subslab in this house were located opposite and adjacent to the wall where the radon concentration was measured, and about equidistant from both subslab and wall radon monitoring locations.

Another way to look at the data is to average the different parameters over time periods that the time-integrating perfluorocarbon tracer gases were deployed in each house (Figures 7-9). The perfluorocarbon tracer (PFT) gas system measures average air flow rates in multizone buildings. This technique measures both infiltration and interzone air flow rates using passive sources and samplers.

Each of the seven research houses has been monitored with PFT systems since the instrumentation packages were installed at the end of October, 1986. The PFT measurements have been made over typically two week periods uninterrupted (except for short time periods during mitigation installation) from the time of installation until late spring to mid-summer, 1986. Figures 7 and 9 extend through May 15th and Figure 8 extends to July 29th. The final calibrations for the PFT technique have been applied to the computation of the air flow rates for these houses.

The method for looking at the PFT data with the other parameters consists of averaging the continuously logged parameters over each time period that the PFT's were active in each house, (which varied slightly between each house). Figures 7 - 9 show this averaged data for homes 1, 5, and 2 (the control house), taking into account the specific PFT time periods for each home. The top box in each figure plots the radon concentrations in the basement and upstairs. The second box displays the basement air infiltration rate (solid line) and the radon source strength (broken line). The third box shows the three logged temperatures at each house: basement, upstairs and outside. The fourth box plots the differential pressures between the basement and the outdoors, subslab, and upstairs (as in Figures 5 and 6). The points on each line represent the average of that parameter using the given PFT time period. The lines across the top of the upper box on each of figures show each PFT time period, which is specific for each house. Shown on the abscissa of the lowest box are the Julian dates.

The seasonal trends are evident, with the outdoor minimum temperature occurring in late January, lowered humidity in the winter, and increased HVAC usage in the winter (the last two parameters are not shown in these graphs). The installation of the mitigation systems in all but the control house (#2) is evident by the decreased levels of radon and larger basement - subslab pressure differences.

The radon source strength displayed in the second box is obtained by assuming the radon behaves similarly to the PFT tracer gas. The relationship between the average emission rate (or source strength) of the tracer gas and the average tracer gas concentration is given by:

Source (PFT in basement) = Average Concentration (PFT in basement) * K,

where K = a function of all of the air flows in the building. In the PFT experiments, the source term is known and the average concentration is measured. The value of K can then be computed and used in the same equation, with radon source and average concentration replacing the PFT terms. Knowing the average concentration of radon in the basement from averaging the Wrenn chamber data, i.e., the top box on the figure, the radon source strength can then be estimated.

Figure 9 displays the radon source rate into the basement for House #2, (the control house, which was not be mitigated until July, 1987) which shows a seasonal trend with a strong winter peak. However, since both the radon source rate and basement infiltration rate (the major determinant of K) increase during the winter, the radon concentration does not have a large winter peak. In fact, there is not a strong seasonal component in the radon concentration at all. House #1 (Figure 7) shows behavior similar to House #2 (Figure 9) for the basement air infiltration rate. Instead of a seasonal dependance, the radon source strength for House #1 decreases and remains low after mitigation. This indicates that the reduced radon levels in the basement are due to decreased source rates brought about by mitigation and not due to increased infiltration levels.

Figures 7 and 8 display some interesting behavior. Houses 1 and 5 are both ranch style homes of about the same size, and their initial, pre-mitigation radon concentrations were similar. The basement infiltration in house 1 is much larger than that in house 5, however, and along with the increased infiltration in house 1 is a larger radon source strength. Recall the above discussion about the two terms which make up the total basement infiltration, i.e., the infiltration from the soil gas and the infiltration from the outdoor air. During SSV operation the infiltration from the soil gas should go to zero. The time point when the SSV system becomes operable coincides with the basement - subslab pressure difference becoming negative. The radon source strengths (and radon concentrations) drop dramatically in both houses during SSV operation. The basement infiltration in house 1 remains high, while in house 5 it is significantly reduced during SSV operation. This implies that the fraction of air infiltrating the basement from the soil gas is much less of the total basement infiltration in house 1 compared to house 5. It could be possible that the total flow of soil gas infiltrating each basement is similar, but that in the leaky house 1 this flow is a much smaller percentage of the total basement infiltration. If this were the case, the radon concentration in the soil gas would have to be higher in house 1 to give similar initial basement radon concentrations.

We know from the Piedmont data, and other studies, that radon concentrations can vary diurnally by as much as a factor of two due to environmental effects. Homeowner interaction with the house can increase this variation much more due to window and door openings and closings. This variation causes a large uncertainty in the use of grab samples to determine radon concentrations. To better quantify the magnitude of this uncertainty the 24-hour average of both the basement and upstairs radon concentrations has been calculated in the seven Princeton/ORNL research homes. Figures 10-15 show these 24-hour averages during the pre-mitigation time period of October through December, 1986. All of the data points from each half hour during this three month period are averaged and plotted as 48 points in the 24 hour day. The line inside each box is the median of the data, and the box contains the inner 50% of the data. The lines which extend out from each side of the box extend to the extremes of the data or 1.5 times the distance from the median line to the edge of the box. The starred values are the outliers, points that lie beyond the above definition.

Figure 10 displays the averaged 24 hour basement radon concentration for the very periodic house 5 discussed above. Figure 11 shows the heater use and Figure 12 shows the upstairs radon concentration. The coupling between these 3 parameters is obvious (as discussed above). When the heater comes on the basement radon is reduced and the upstairs radon increases by about 10 pCi/L, on the average. Figures 13 through 15 are similar graphs for house 3 in the study. Neither house 3, nor any of the other homes in the study showed the same periodicity as house 5, although some of the other homes displayed a somewhat periodic nature in one or more of the other parameters (see Figure 15 for house 3 HVAC use). One of the more striking aspects of the plots for house 3 and the other 5 homes shown is the constant nature of the median and inner 50% of the data on radon concentrations over the 24 hour period. For high indoor radon concentrations, a grab sample will give a reasonable indication of the magnitude of the indoor radon concentration (as long as the homeowner has not been airing the house). For low indoor radon concentrations, grab sampling is not a useful diagnostic tool because of the associated error.

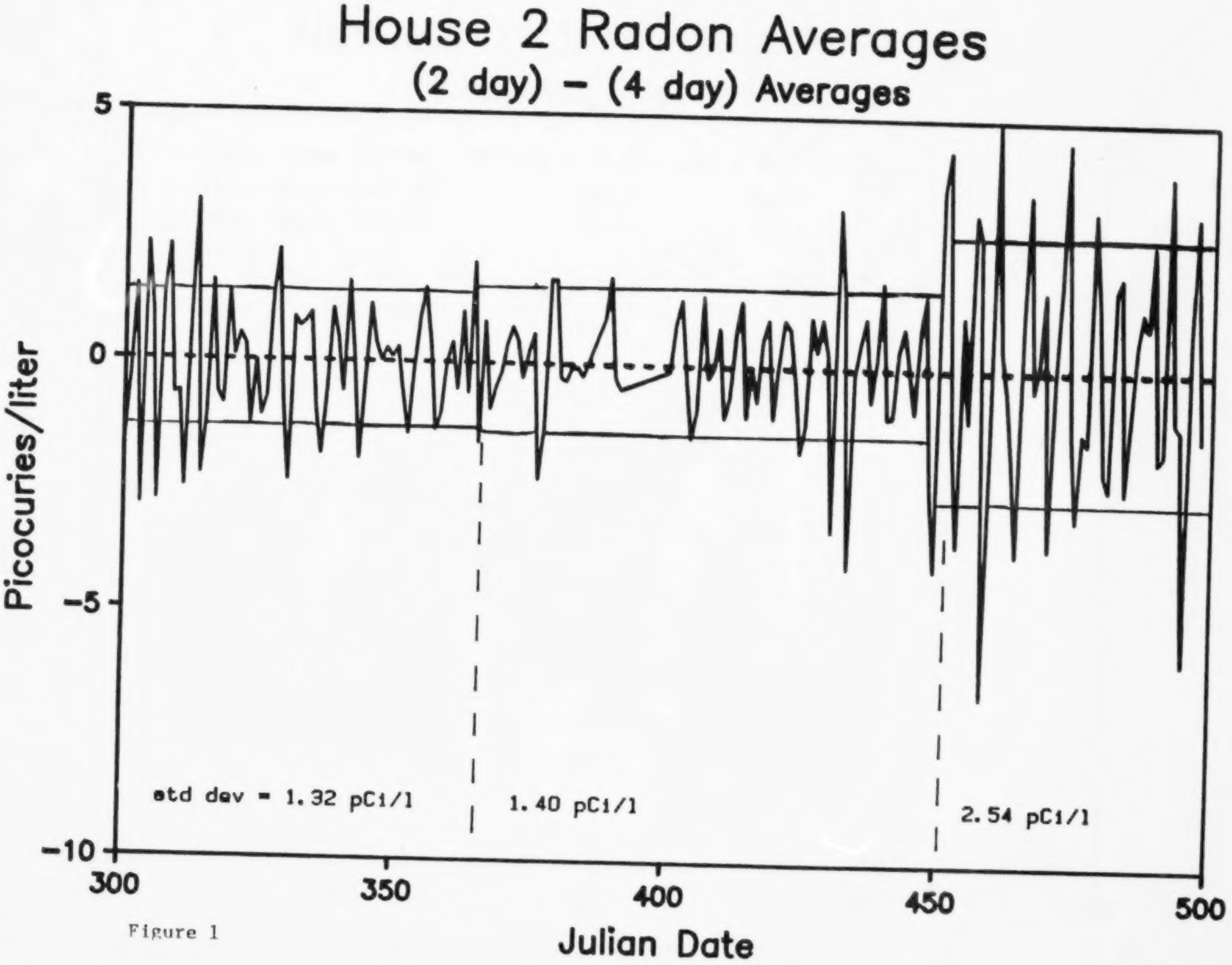

House 2 Radon Averages
(2 day) - (4 day) Averages
Picocuries/liter
5
0
-5
-10
300
350
400
450
500
Julian Date
atd dev = 1.32 pCi/l
1.40 pCi/l
2.54 pCi/l

Figure 1

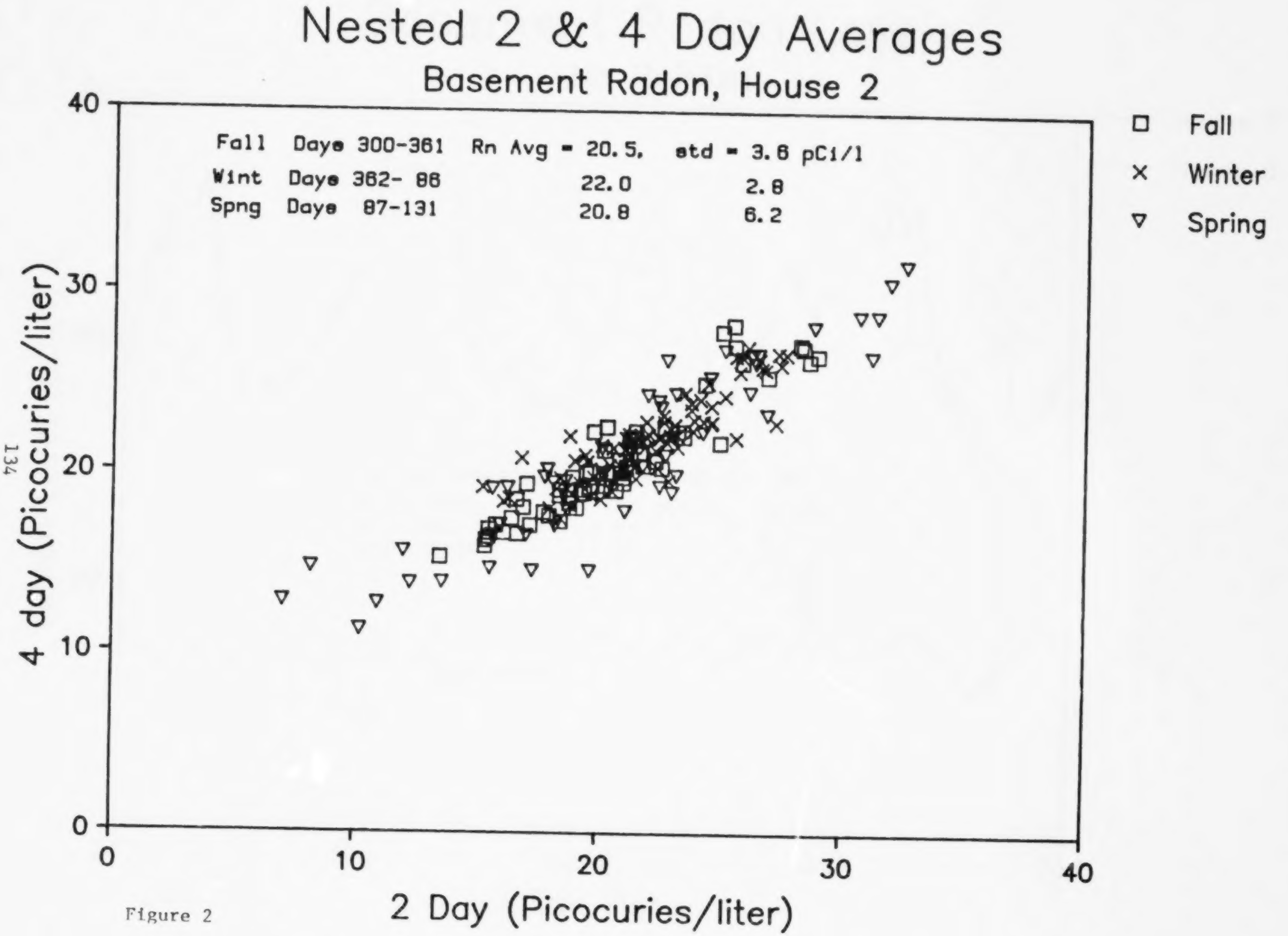
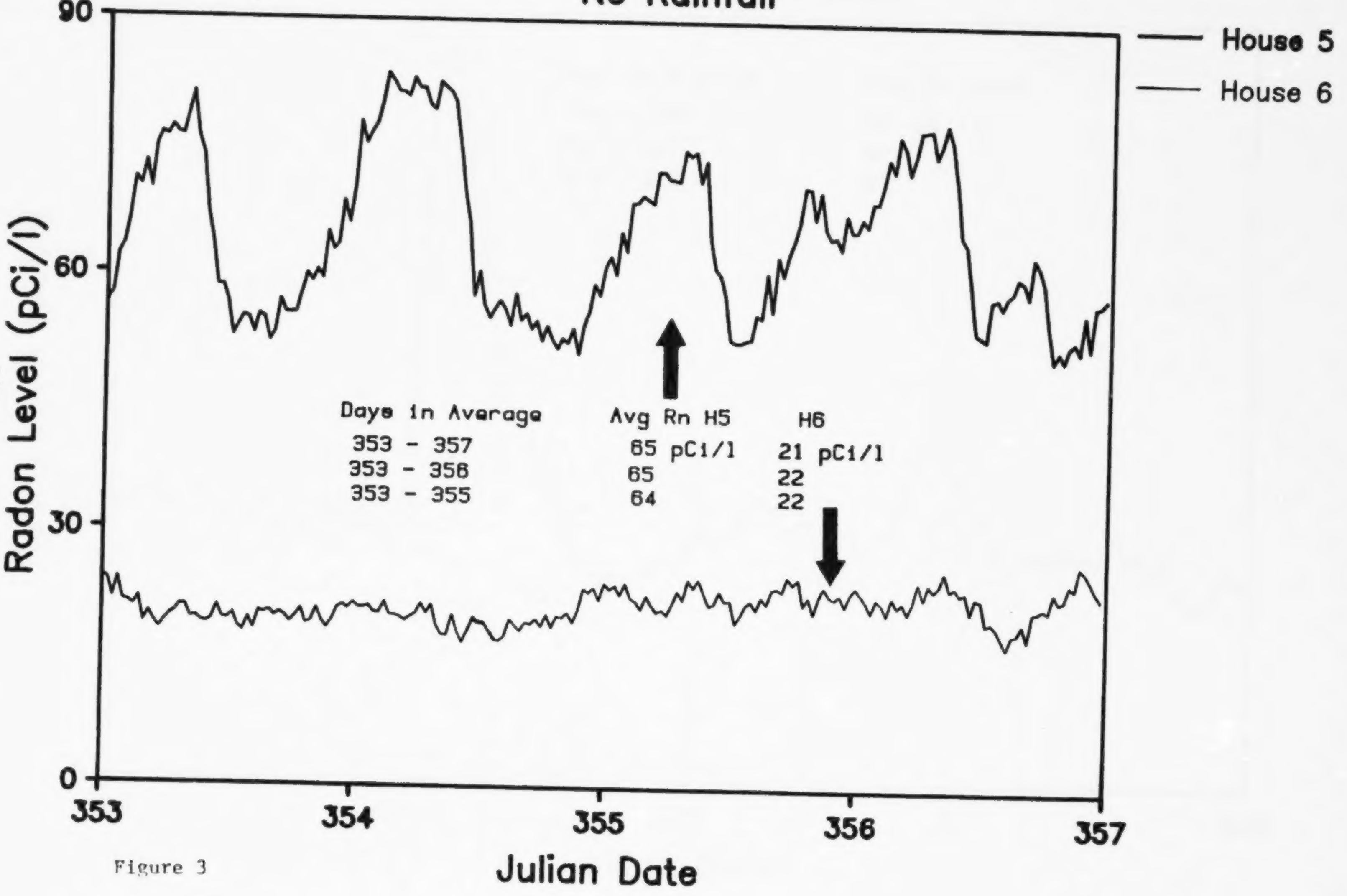
Nested 2 & 4 Day Averages
Basement Radon, House 2
Fall Days 300-361 Rn Avg = 20.5, std = 3.6 pCi/l
Wint Days 362- 86 22.0 2.8
Spng Days 87-131 20.8 6.2
□ Fall
× Winter
▽ Spring
4 day (Picocuries/liter)
0
10
20
30
40
2 Day (Picocuries/liter)
0
10
20
30
40

Figure 2

Basement Radon Levels

No Rainfall



Days in Average	Avg Rn H5	H6
353 - 357	65 pCi/l	21 pCi/l
353 - 356	65	22
353 - 355	64	22

Figure 3

Basement Radon Levels

House 7, Rainfall Period

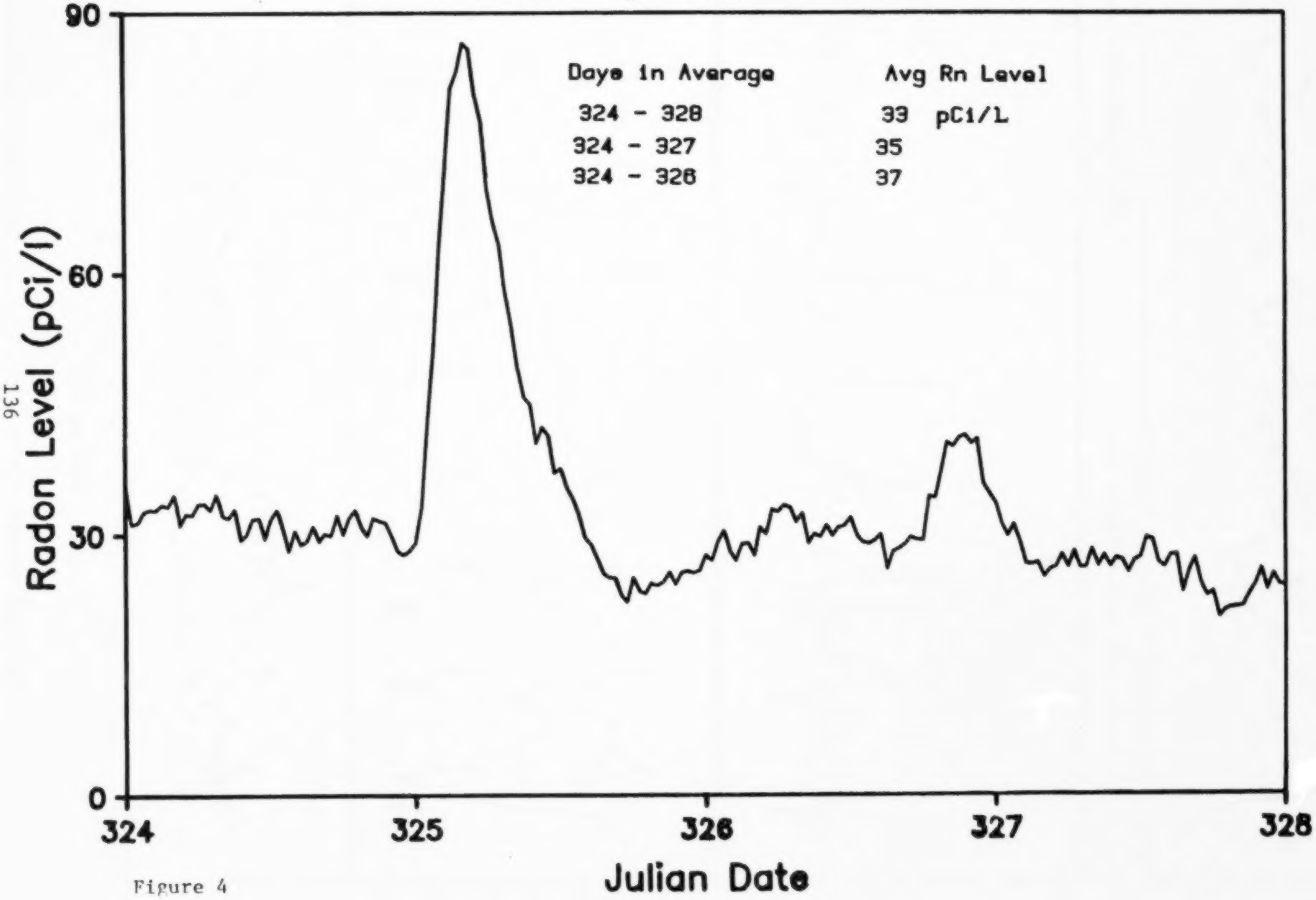


Figure 4

PU/CEES RN87

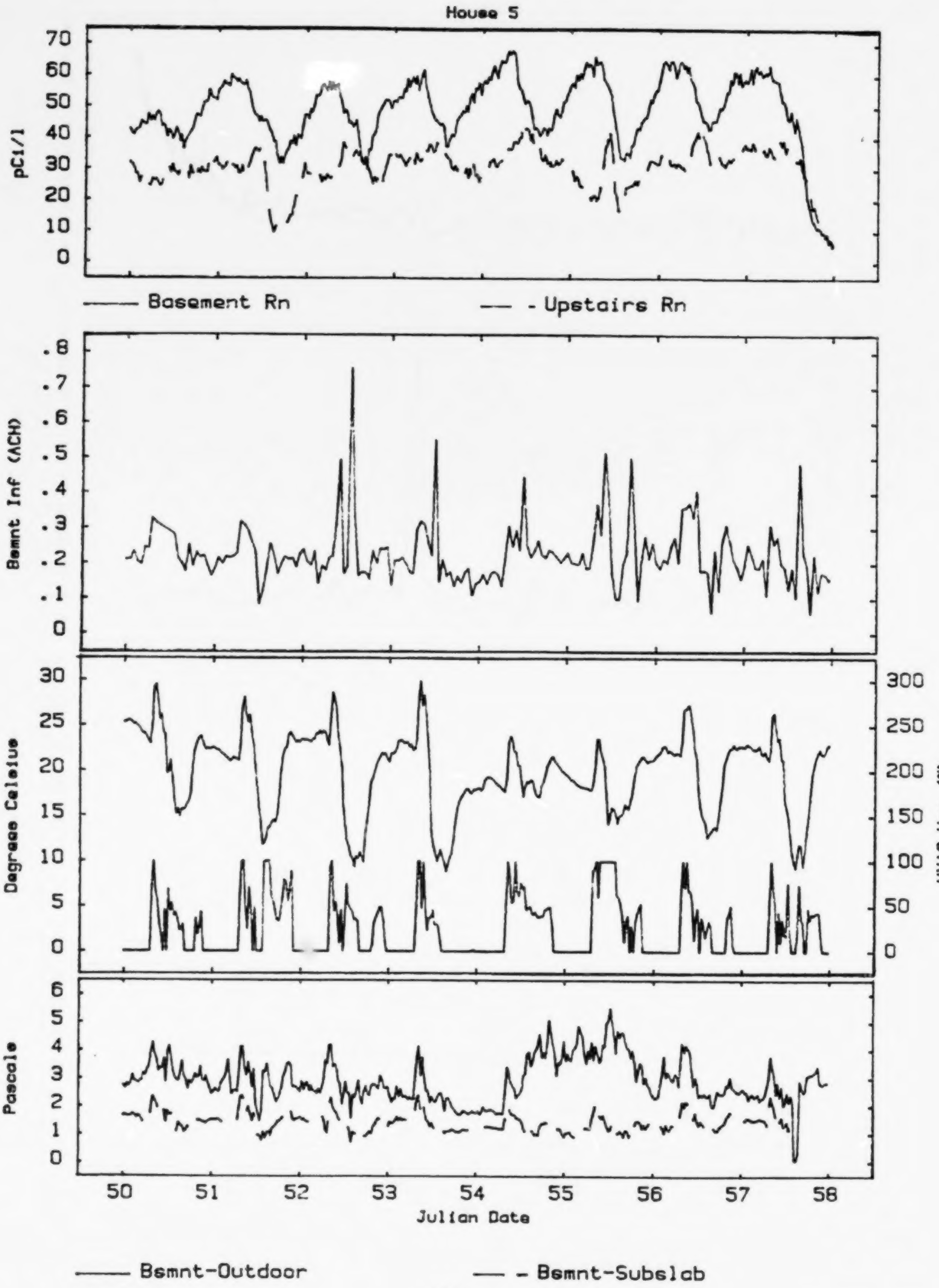

House 5
pCi/l
70
60
50
40
30
20
10
0
Basement Rn
- Upstairs Rn
Bsmnt Inf (ACH)
.8
.7
.6
.5
.4
.3
.2
.1
0
Degrees Celsius
30
25
20
15
10
5
0
HVAC Use (%)
300
250
200
150
100
50
0
Pascals
6
5
4
3
2
1
0
50
51
52
53
54
55
56
57
58
Julian Date
Bsmnt-Outdoor
- Bsmnt-Subslab

Figure 5

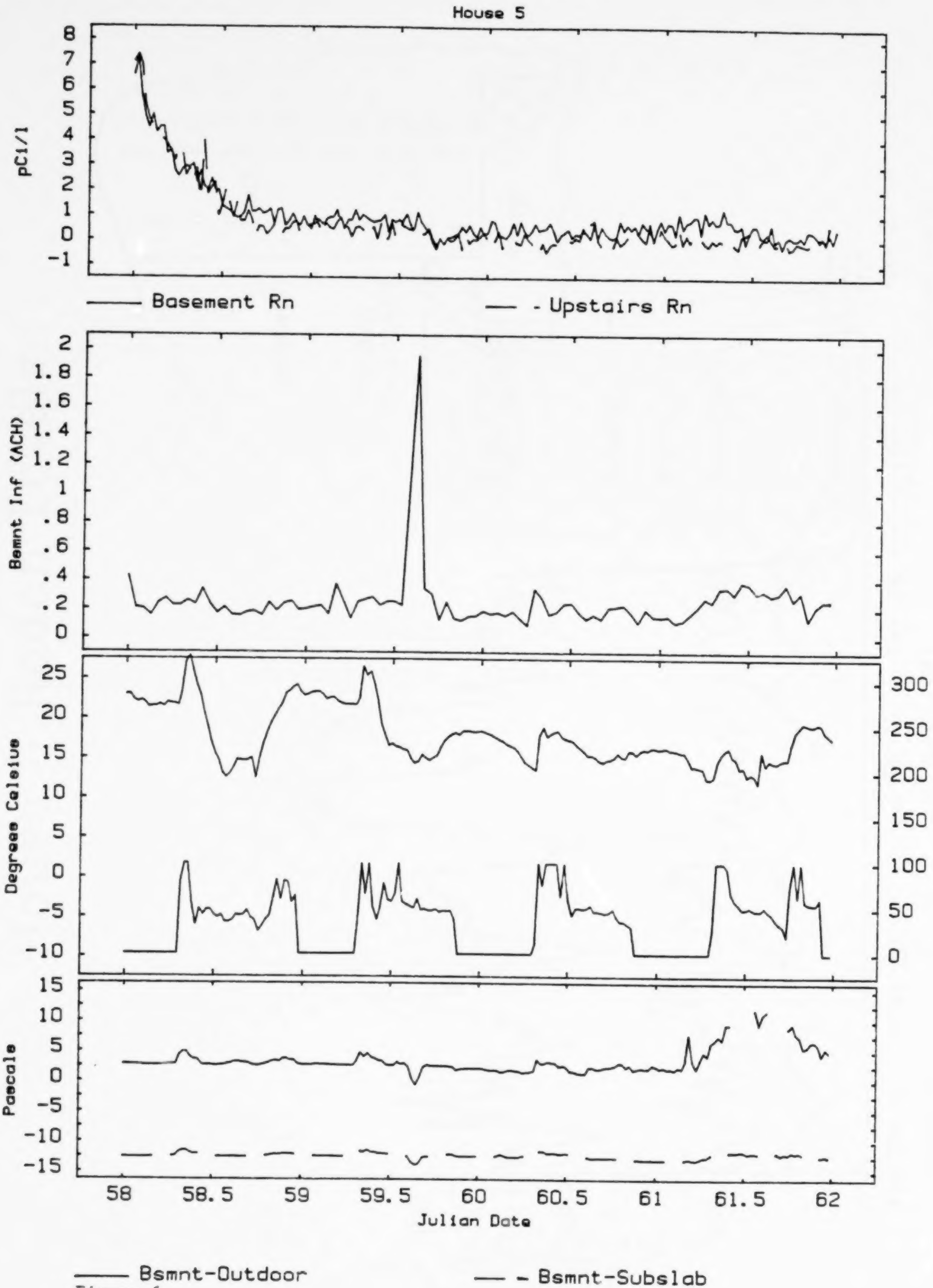

House 5
pCi/l
8
7
6
5
4
3
2
1
0
-1
Basement Rn
- Upstairs Rn
Bsmnt Inf (ACH)
2
1.8
1.6
1.4
1.2
1
.8
.6
.4
.2
0
Degrees Celsius
25
20
15
10
5
0
-5
-10
HVAC Use (%)
300
250
200
150
100
50
0
Pascals
15
10
5
0
-5
-10
-15
58
58.5
59
59.5
60
60.5
61
61.5
62
Julian Date
Bsmnt-Outdoor
- Bsmnt-Subslab

Figure 6

House 5 Radon Levels

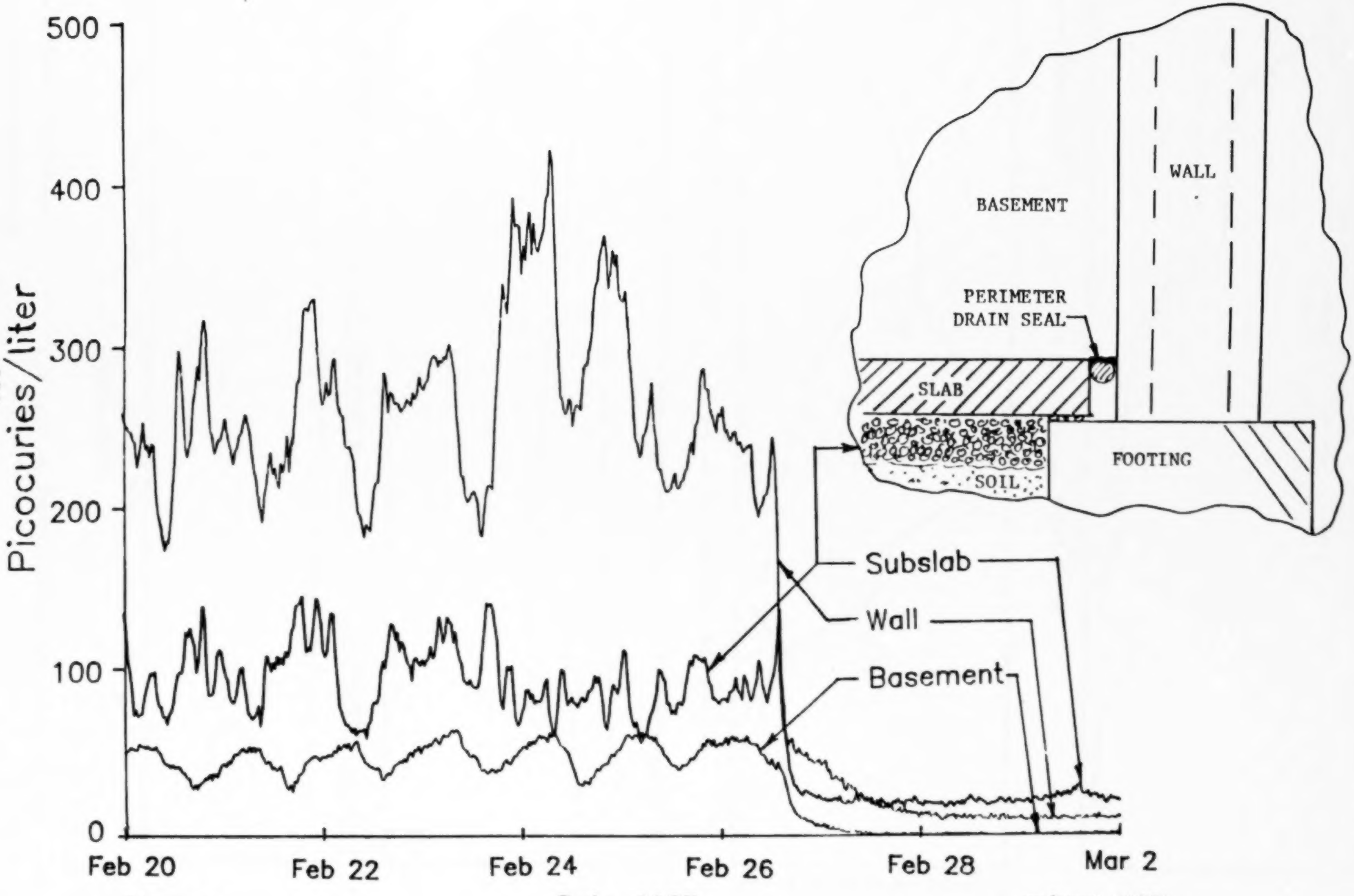


Figure 6a

PU/CEES RN875

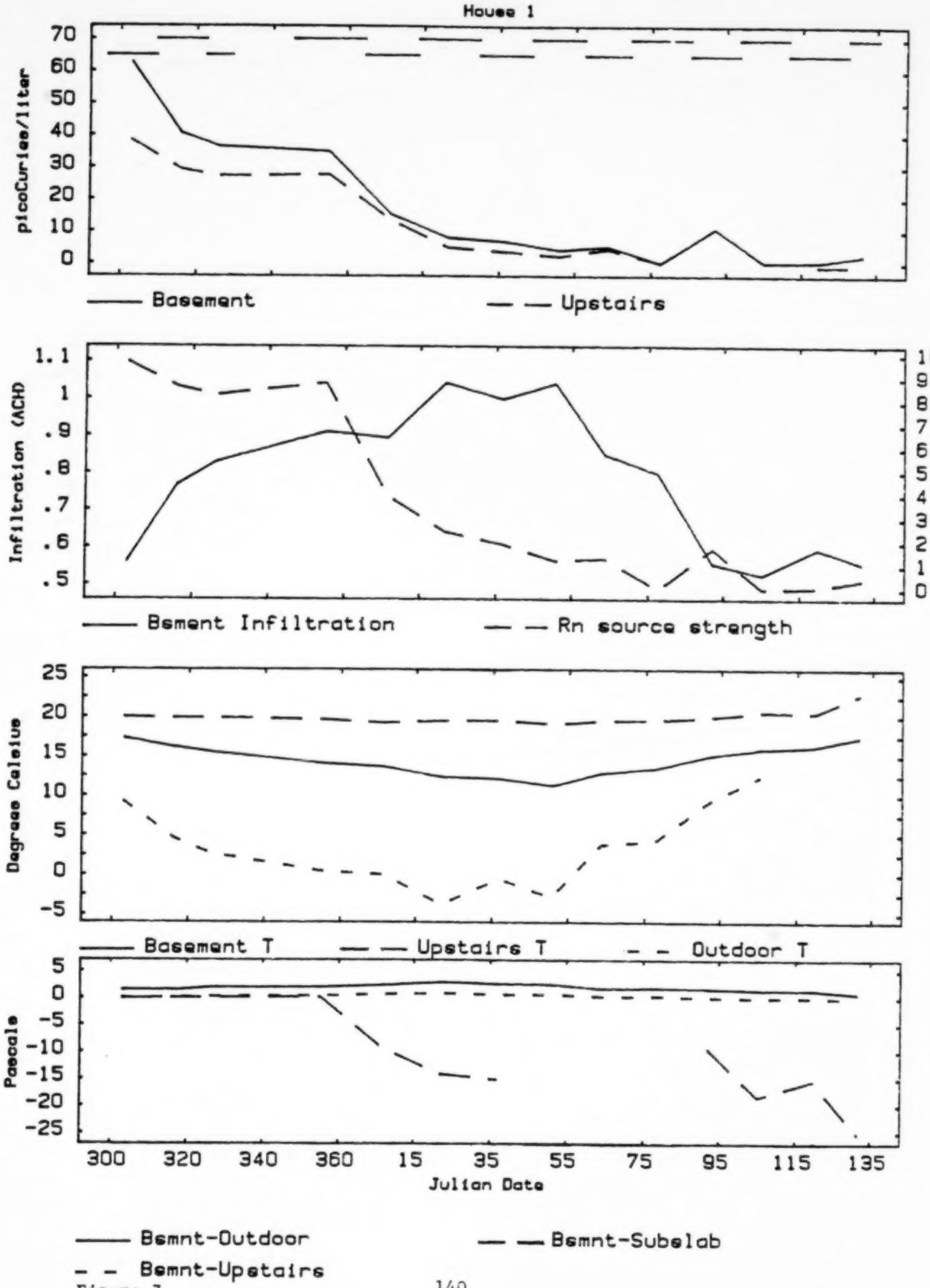

House 1
picoCuries/liter
70
60
50
40
30
20
10
0
Basement
Upstairs
Infiltration (ACH)
1.1
1
.9
.8
.7
.6
.5
microCuries/hour
10
9
8
7
6
5
4
3
2
1
0
Bsment Infiltration
Rn source strength
Degrees Celsius
25
20
15
10
5
0
-5
Basement T
Upstairs T
Outdoor T
Pascals
5
0
-5
-10
-15
-20
-25
300
320
340
360
15
35
55
75
95
115
135
Julian Date
Bsmnt-Outdoor
Bsmnt-Subslab
Bsmnt-Upstairs

Figure 7

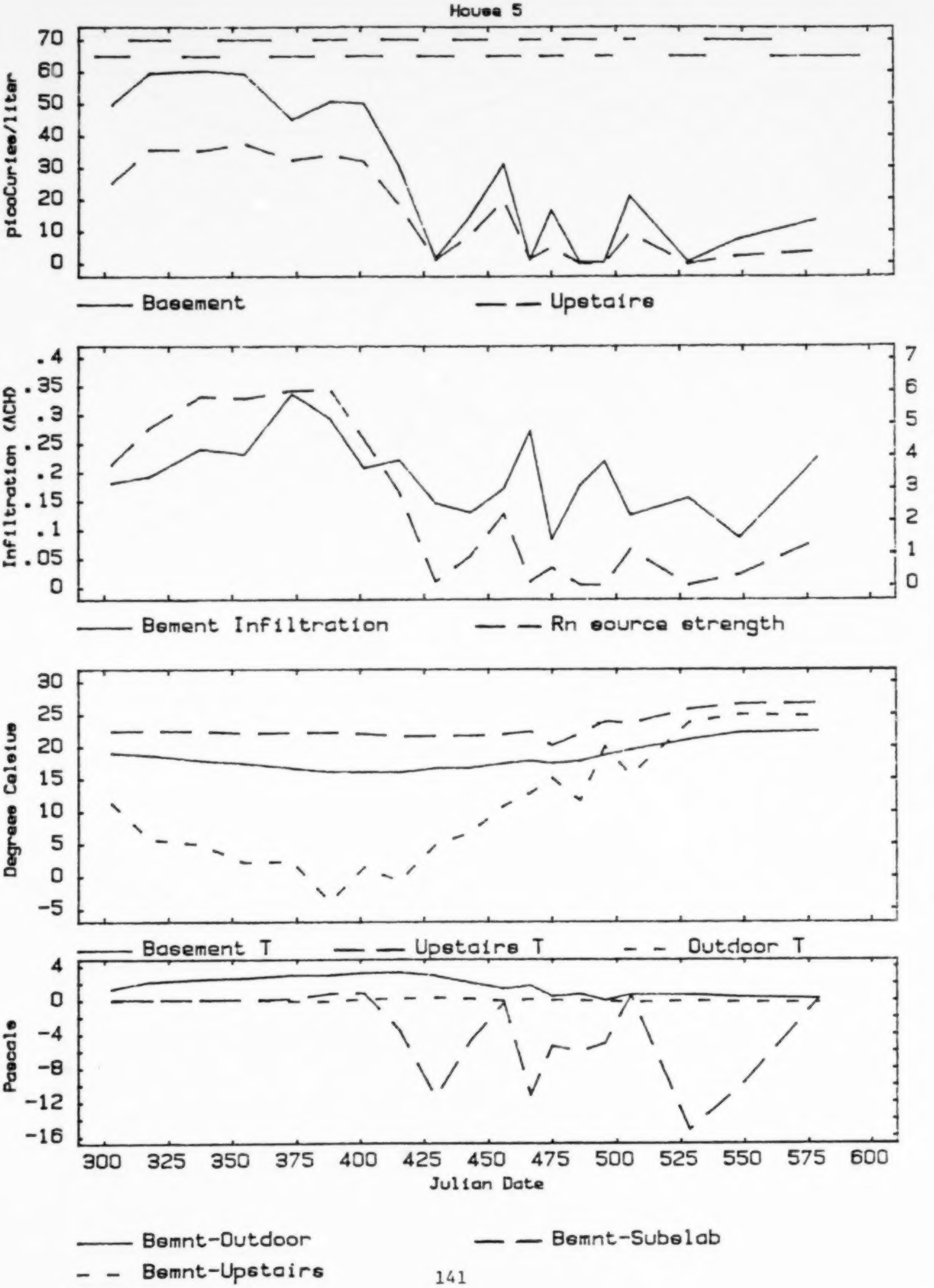

House 5
picoCuries/liter
70
60
50
40
30
20
10
0
Basement
Upstairs
Infiltration (ACH)
.4
.35
.3
.25
.2
.15
.1
.05
0
microCuries/hour
7
6
5
4
3
2
1
0
Bement Infiltration
Rn source strength
Degrees Celsius
30
25
20
15
10
5
0
-5
Basement T
Upstairs T
Outdoor T
Pascals
4
0
-4
-8
-12
-16
300
325
350
375
400
425
450
475
500
525
550
575
600
Julian Date
Bemnt-Outdoor
Bemnt-Subslab
Bemnt-Upstairs

Figure 8

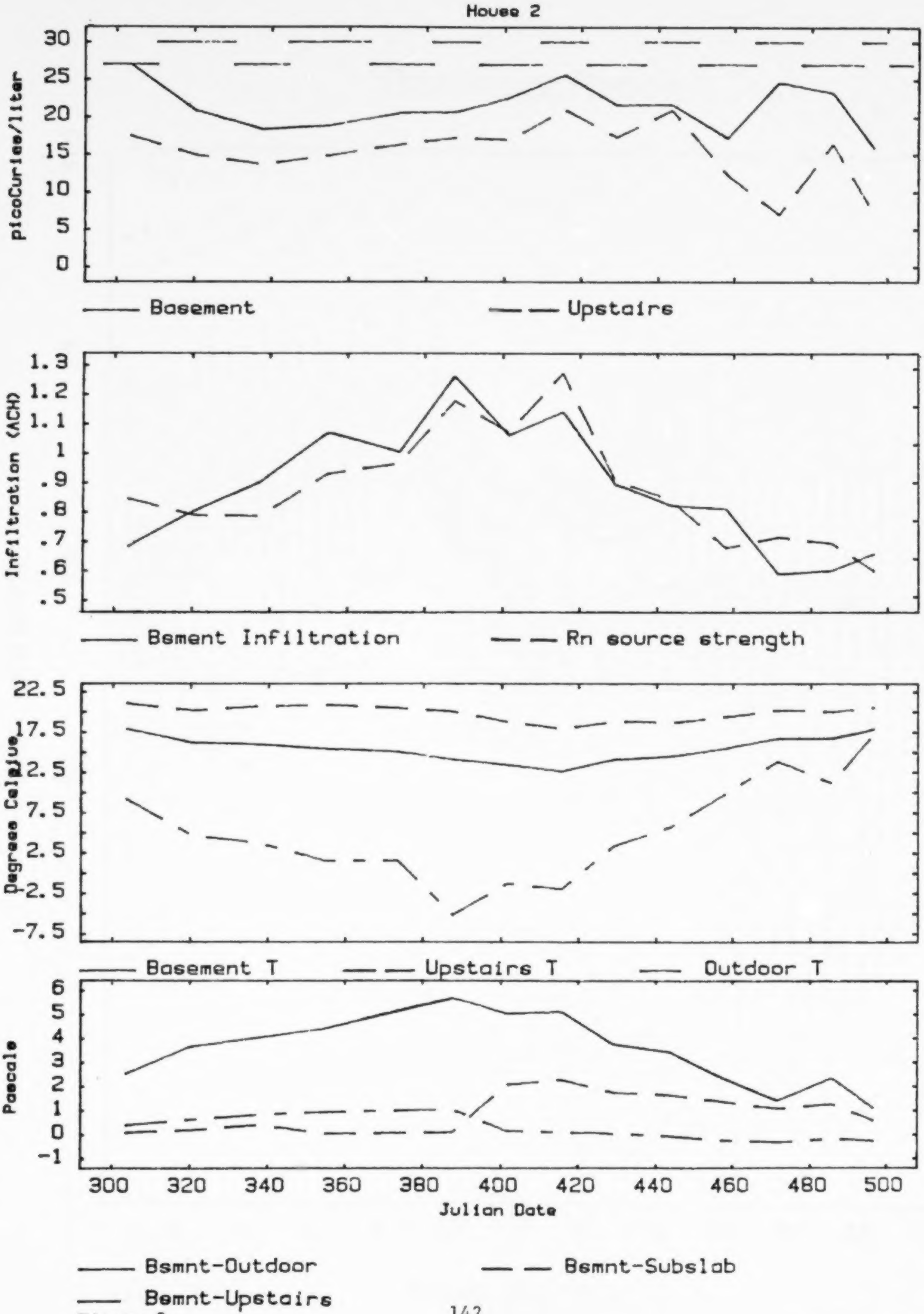
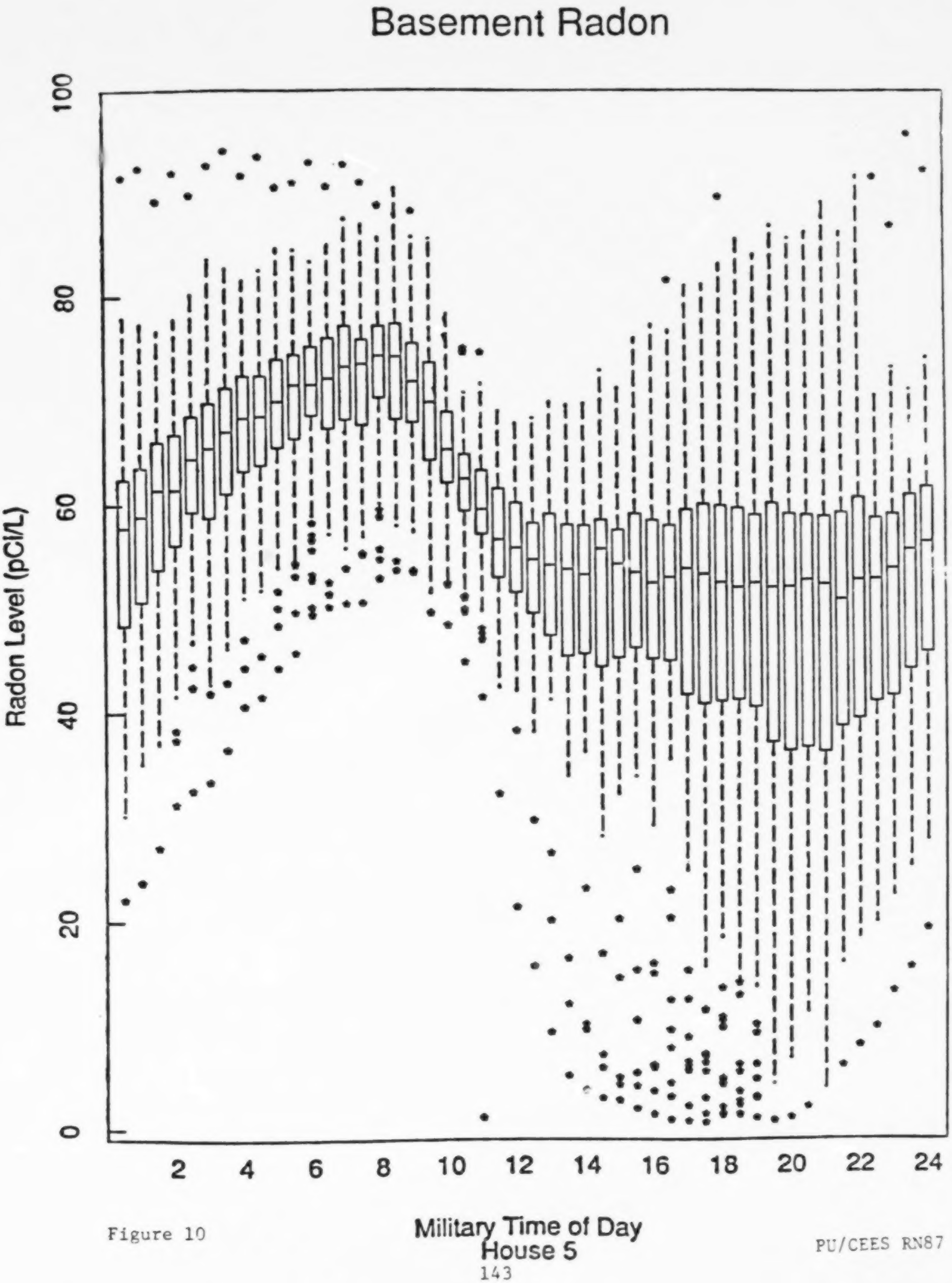

House 2
picoCuries/liter
30
25
20
15
10
5
0
Basement
Upstairs
Infiltration (ACH)
1.3
1.2
1.1
1
.9
.8
.7
.6
.5
microCuries/hour
9
8
7
6
5
4
3
Bsment Infiltration
Rn source strength
Degrees Celsius
22.5
17.5
12.5
7.5
2.5
-2.5
-7.5
Basement T
Upstairs T
Outdoor T
Pascals
6
5
4
3
2
1
0
-1
300
320
340
360
380
400
420
440
460
480
500
Julian Date
Bsmnt-Outdoor
Bsmnt-Subslab
Bsmnt-Upstairs

Figure 9



Basement Radon
Radon Level (pCi/L)
0
20
40
60
80
100
2
4
6
8
10
12
14
16
18
20
22
24
Military Time of Day
House 5

Figure 10

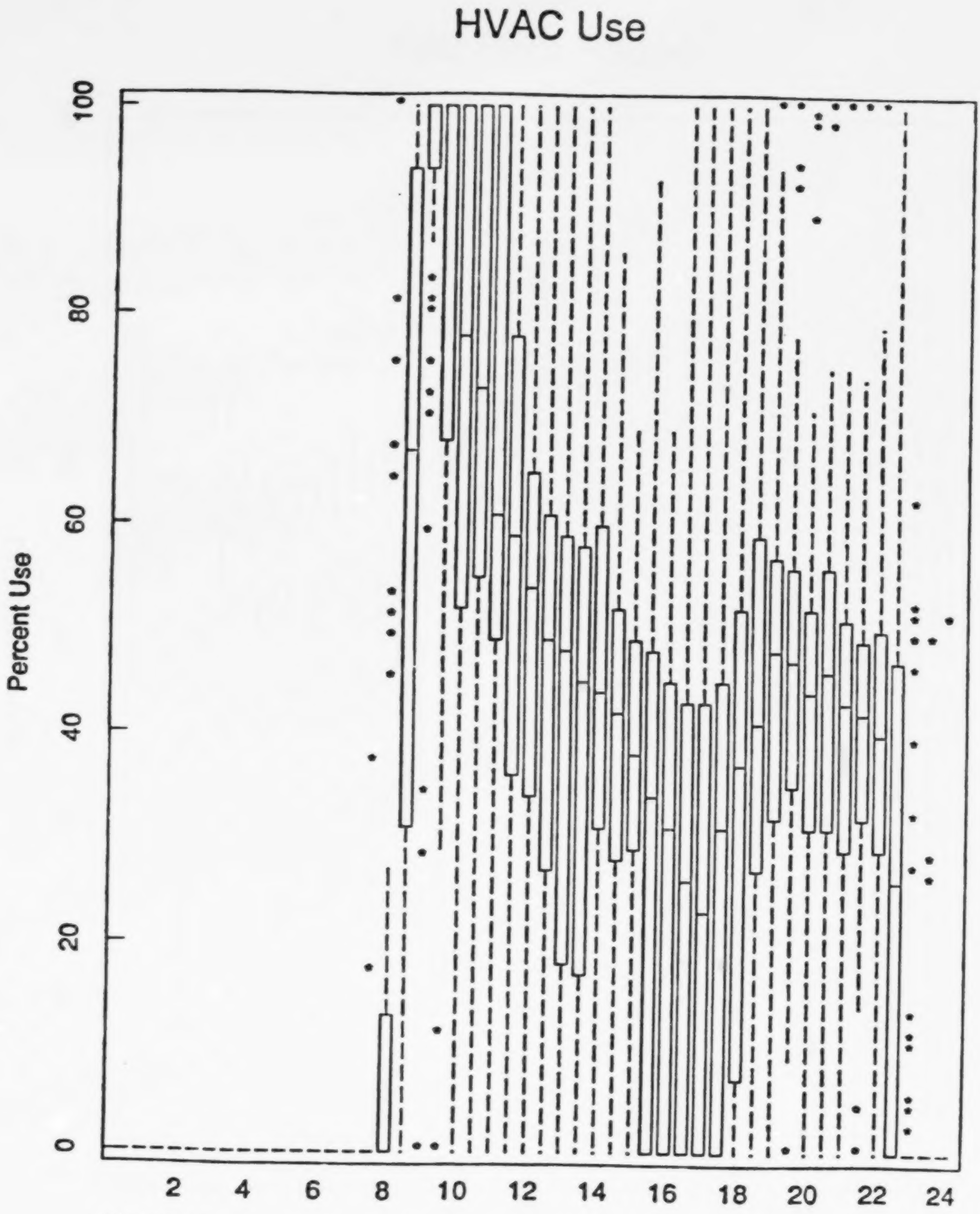

HVAC Use
Percent Use
0
20
40
60
80
100
2
4
6
8
10
12
14
16
18
20
22
24

Figure 11

Military Time of Day
House 5

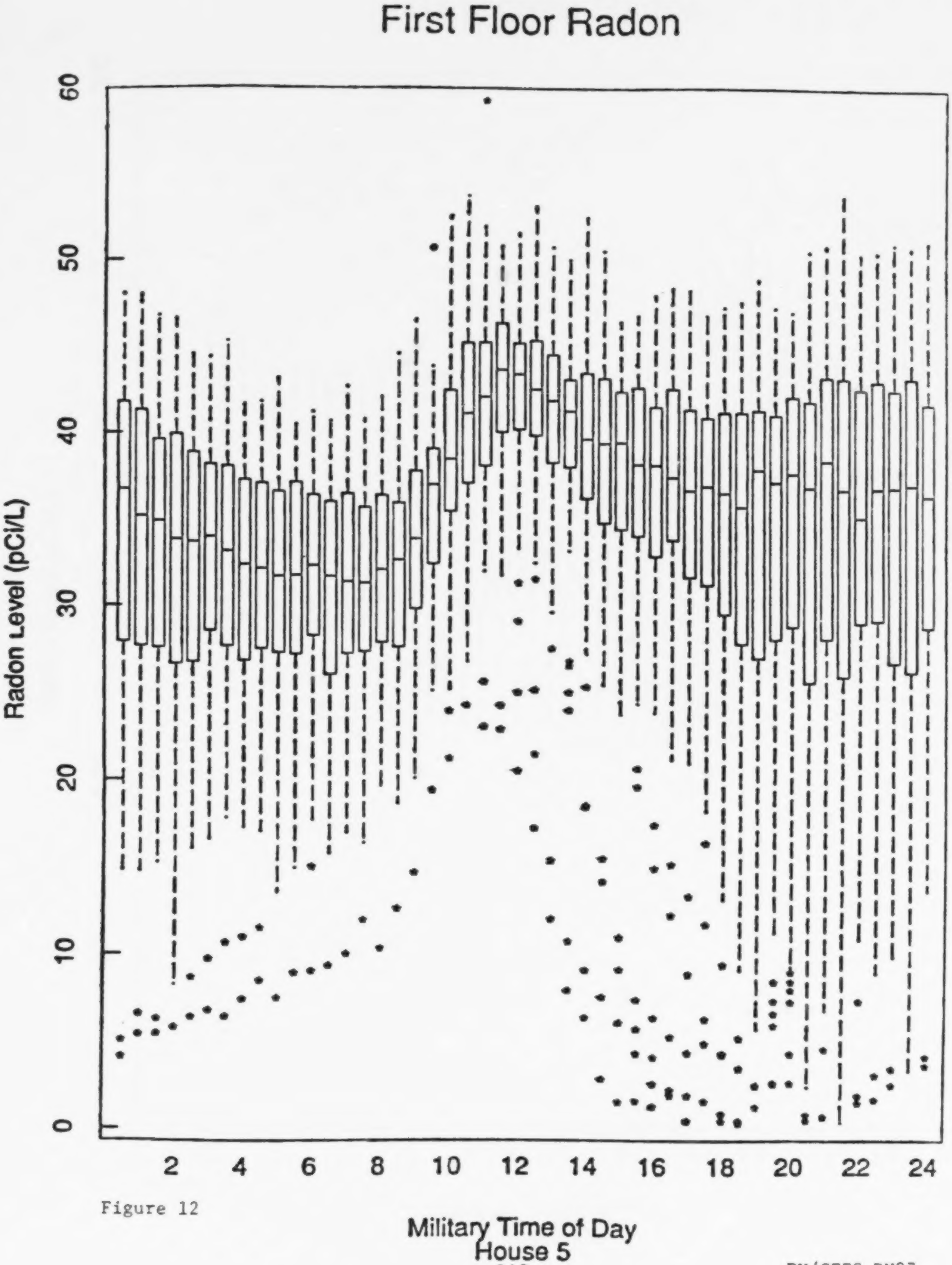

First Floor Radon
Radon Level (pCi/L)
0
10
20
30
40
50
60
2
4
6
8
10
12
14
16
18
20
22
24
Military Time of Day
House 5

Figure 12

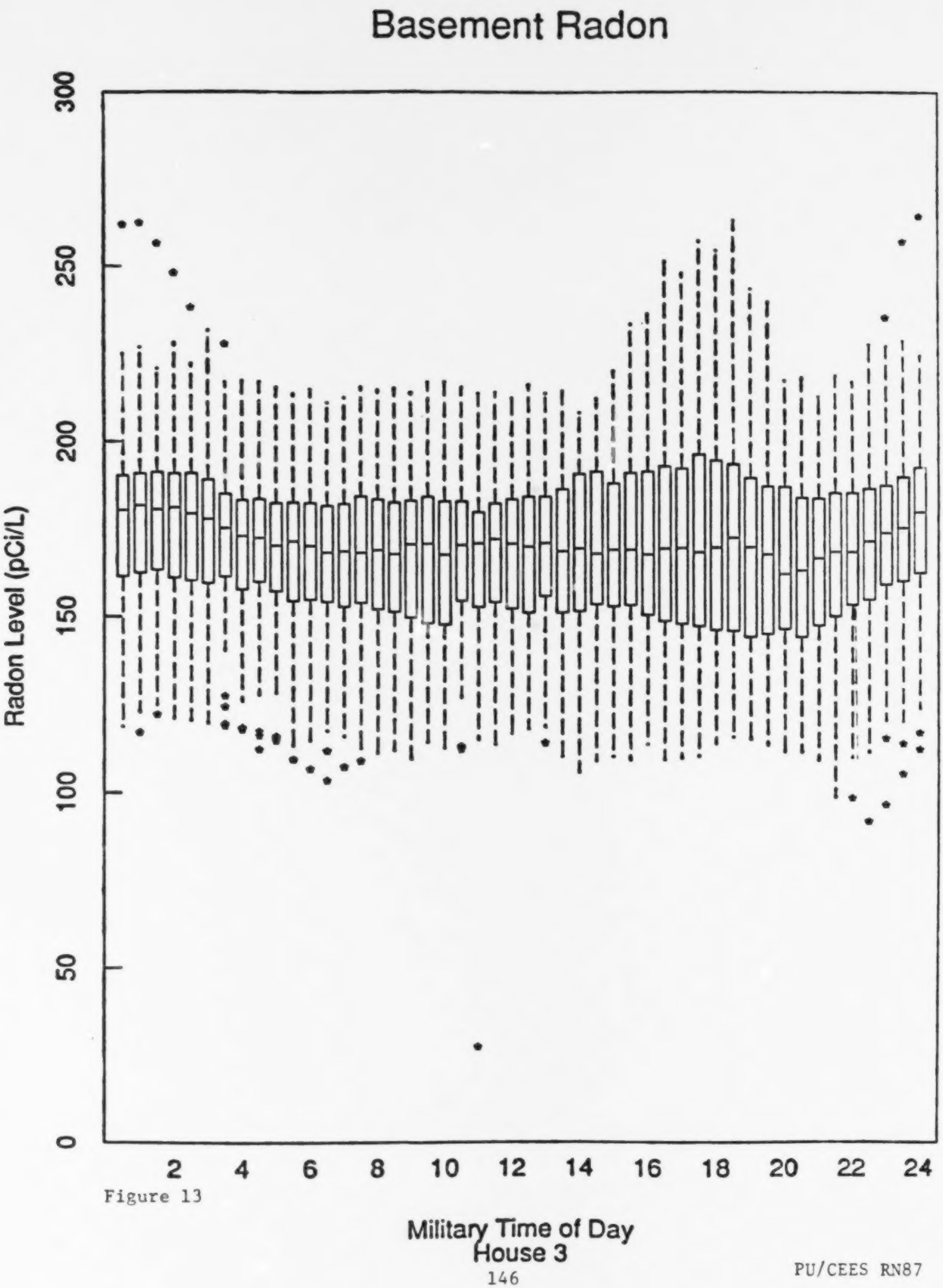

Basement Radon
Radon Level (pCi/L)
0
50
100
150
200
250
300
2
4
6
8
10
12
14
16
18
20
22
24
Military Time of Day
House 3

Figure 13

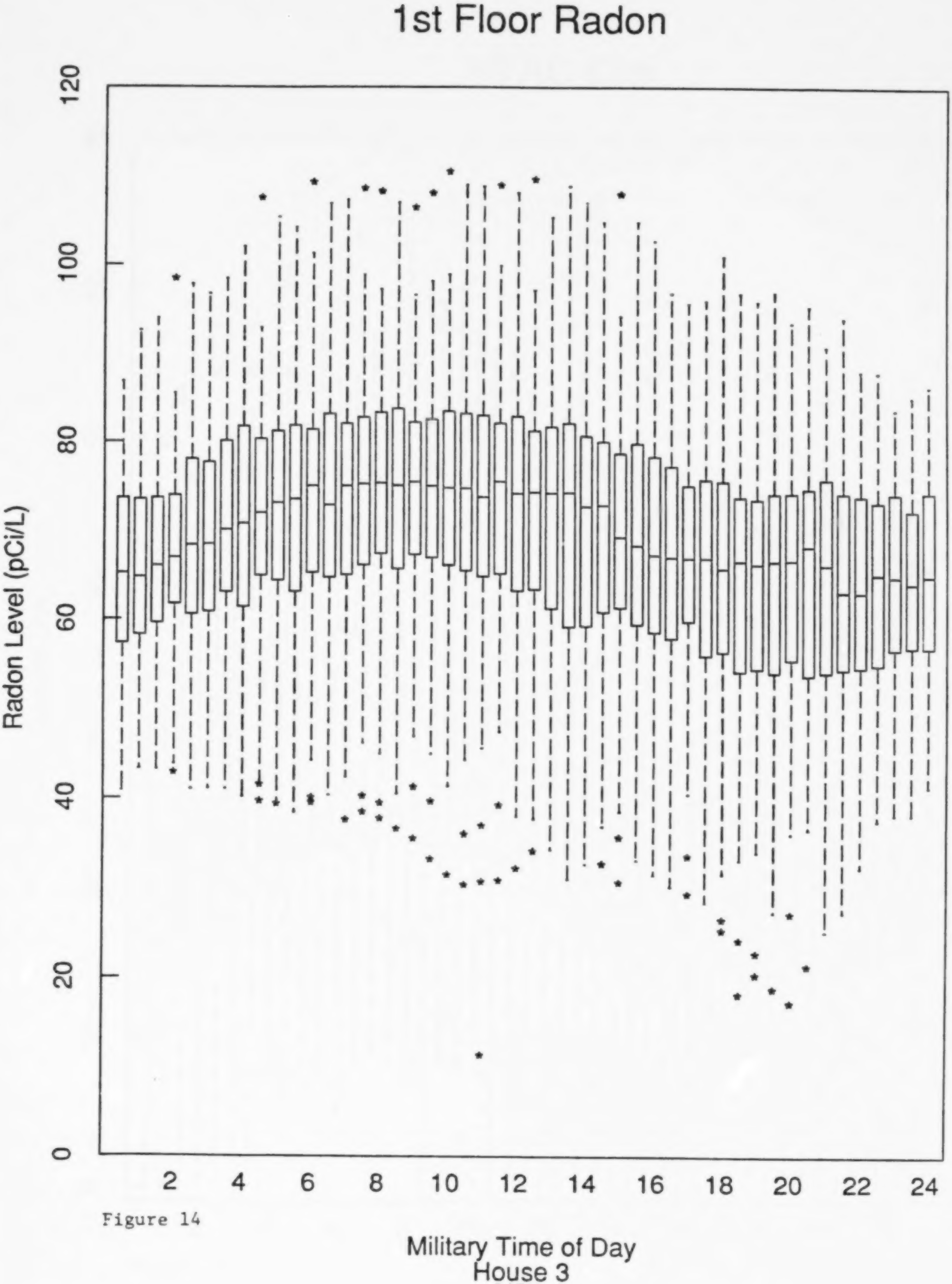

1st Floor Radon
Radon Level (pCi/L)
0
20
40
60
80
100
120
2
4
6
8
10
12
14
16
18
20
22
24
Military Time of Day
House 3

Figure 14

HVAC Use

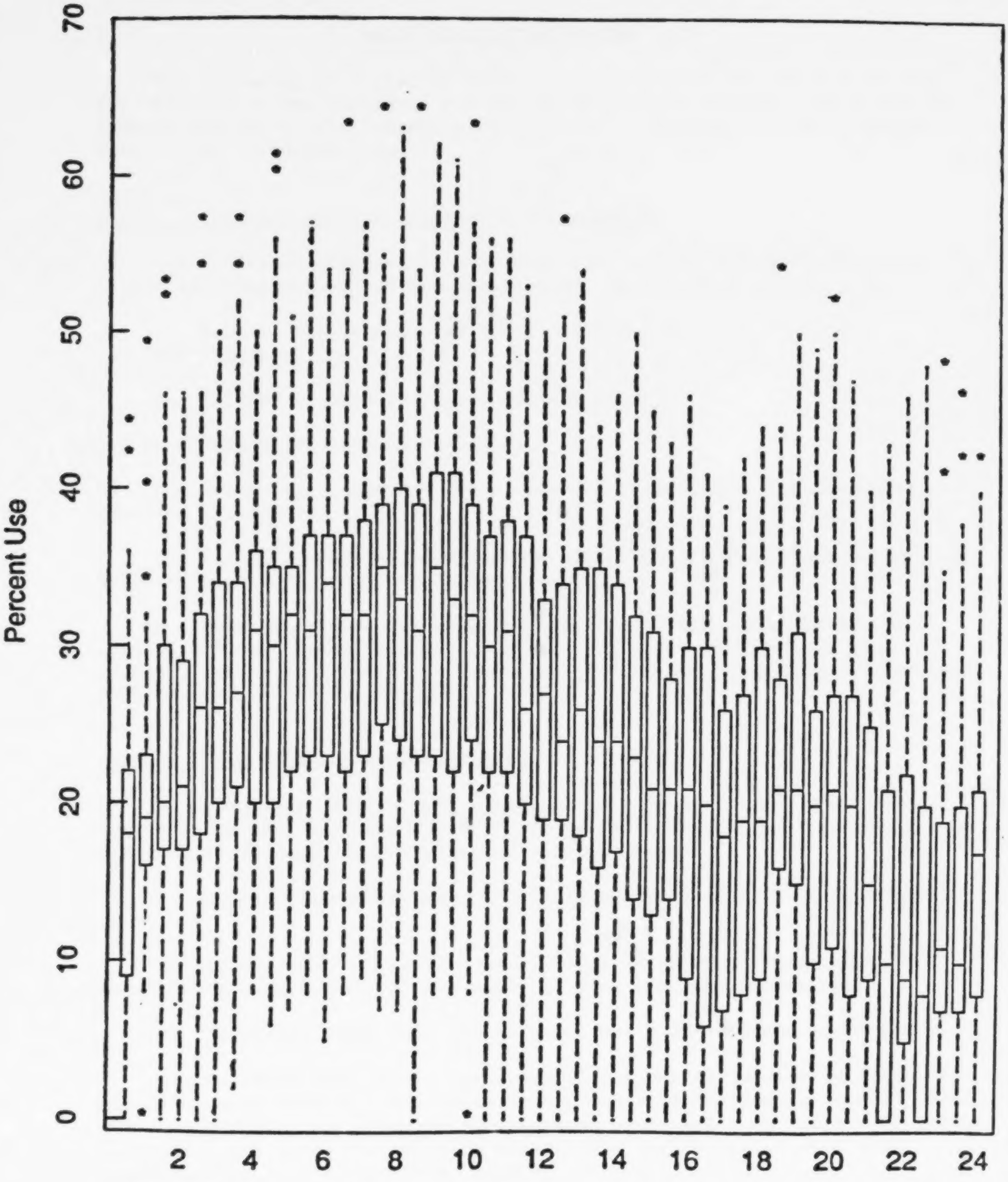


Figure 15

Military Time of Day
House 3

PART D

RADON DIAGNOSTICS MASTER LIST

The following is a list of diagnostic techniques that have been used for determining the existence and extent of a radon problem. What type of information and to what extent each of these techniques have been useful will not be discussed here.

Phase 1. Initial Problem Assessment Diagnostics.

The following diagnostic techniques can be used for characterizing either existing structures and their sites, or new construction sites.

a. Mobile radiological van for radiation scans both outdoors and indoors.

b. Mapping of soil gas radon concentrations.

c. Mapping of soil permeability.

The following diagnostic techniques can be used for characterizing existing structures.

a. Visual inspection of structure with completion of questionnaire on building and house occupancy characteristics.

b. Determine radon concentrations in one or many zones within the structure. Many techniques are available for doing this such as grab samples, carbon cannisters or alpha track for integrated samples, continuous monitors, working level monitors.

Phase 2. Pre-mitigation Diagnostics.

a. Natural condition grab sample in each zone and in holes drilled into the subslab, into the hollow block walls if they exist, or through any other existing membrane suspected as a radon source.

b. Repeat a. under mechanical -10 Pa depressurization using a blower door.

c. Blower door test of the whole house or parts of house where possible or interesting, to evaluate building envelope tightness.

d. IR scan of each room, to evaluate building envelope tightness.

e. Basement/subslab and basement/wall communications using single or variable speed motor to pressurize or depressurize the subslab area. Check pressure differentials between the basement and subslab on walls through the test holes and check air velocity through the test holes to determine communication from one point to another.

f. Check pressure differentials between the basement/subslab and basement/upstairs as appliances (dryers, exhaust fans, furnace fans, etc.) are cycled on and off.

g. Tracer gas measurements used to evaluate air exhange rates and flows between zones.

Phase 3. Mitigation Installation Diagnostics.

a. Tracer gas measurements to determine leakage or backdraft of exhaust.

b. Adjust dampers for balanced air flow within the mitigation system.

c. Check the balance by measuring pressure differentials and the velocities at key points in the mitigation system.

d. Integrity check of any building envelope components penetrated by mitigation system.

Phase 4. Post-Mitigation Diagnostics.

a. Determine radon concentrations in different zones in the building.

b. Determine fan speed required for efficient radon removal, consider energy aspects.

c. Check furnace draft for air flow direction, to insure that combustion products are exiting properly.

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These references have been supplied by Dr. Allan Tanner.

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Science of the Total Environment, v. 45, p. 219-226

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Surface area determinations and diffusion measurements by means of radioactive inert gases. Part III. The process of radioactive emission from disperse systems. Conclusions pertaining to the evaluation of EP (emanating power) measurements and the interpretation of results [in German]:
Zeitschr. Physik. Chemie, v. 192, no. 1/2, p. 1-55 in English translation, East Orange, New Jersey, Assoc. Tech. Services, no. 43G7G, 38 p. [1955]

Radon Contributions from the Mining Industry

Bates, Robert C., 1977
Rock sealant restricts falling barometer effect:
Mining Engineering, Dec. 1977, p. 38-39
"These analyses demonstrate that radon contamination resulting from a change in barometric pressure is reduced by a rock [sealant] coating. This, however, is not the major fact to be kept in mind. More important is that, despite the imperfection in the coatings, the radon concentration in the mine atmosphere was reduced through the use of coatings by more than 70% from an average of 480 to 140 [pCi/L]."

Bates, Robert C., 1977
Sealants restrict barometric pressure effects:
Mining Engineering, 29(12); 38-39

Bates, Robert C., 1980
Time dependent radon loss from small samples:
Health Physics, 39: 799-801
In connection with a study of the effect of moisture on the radon emanation coefficient in small uranium ore samples, the question arose about the time needed to reach a steady-state flux of radon from a sample after opening of its sealed storage and counting can. It was felt intuitively that the time required to reach equilibrium would depend on the pore-filling fluid and the diffusion coefficient. No evaluation of this effect was found in the literature. A previously developed analytical code was used with a cylindrical model 9.2 cm long and 3.843 cm in radius, 0.2 porosity, 1E-7 cm^2 permeability, 300 K, and pore-fluid viscosity of 1.8E-4 g/cm-s. The periods required to reach a steady-state flux were computed to be 0.25, 1.25, 10.0, 70.0, and >100.0 hours, respectively, for diffusion coefficients of 1E-2, 1E-3, 1E-4, 1E-5, and 1E-6 cm^2/s.

Bates, Robert C., and John C. Edwards, 1978
Radon emanation relative to changing barometric pressure and physical constraints, in Conference on Uranium Mining Technology, Second, Reno, Nev., November 13-17, 1978:
Background is given on the various equations used to describe diffusion and convective flow of radon in porous media. Equations developed by the Bureau of Mines for modeling diffusion and Darcy flow through multilayered porpus media are described briefly and examples of their use are given. Cases evaluated include overpressurization, underpressurization, and cyclic pressurization of different-sized ore bodies. Another part of the analysis deals with the effect of pinholes on the effectiveness of a radon barrier coating.

Bates, Robert C., and John C. Edwards, 1981
The effectiveness of overpressure ventilation: a mathematical study, in Gomez, Manuel, ed., Radiation Hazards in Mining: Control, Measurement, and Medical Aspects, International Conference, Golden, Colo., October 4-9, 1981:
Golden, CO, Colorado School of Mines, Chap. 24, p. 149-154
Results are given of a mathematical study of overpressurization ventilation effects in underground uranium mines. The mathematics and computer

codes make it possible to analyze many facets of transient and steady-state radon diffusion with Darcy flow. Rapid changes in radon flux occur after imposing a pressure differential across the model. Flux into the model mine drops to near zero and then increases to the steady state level, while the sink flux increases rapidly and then drops slightly to the steady-state level. Magnitudes of mine flux decreases and sink flux increases are dependent upon the distance from the mine to sink, permeability, and the amount of overpressure.

Bates, Robert C., and John C. Franklin, 1977
U. S. Bureau of Mines radiation control research, in Conference on Uranium Mining Technology, Reno, Nev., April 25-29, 1977:
Efforts by the Bureau of Mines to measure and reduce harmful concentrations of radioactive gas in uranium mines are discussed. Equipment has been developed for simultaneous monitoring of radon and radon daughters, temperature, relative humidity, absolute pressure, and air velocity. The effects of changes in weather conditions, ventilation, and mining methods on the mine atmosphere can therefore be evaluated. Addition of water to the rock substantially increases the radon emanation from rock walls. Control methods being evaluated include overpressurization, cyclic ventilation, bulkheading, backfilling with tailings, and application of sealants to the mine rock.

Bates, R. C., and R. L. Rock, 1962
Estimating Daily Exposures of Underground Uranium Miners to Airborne Radon-Daughter Products:
U. S. Bur. Mines Rept. Investigations 6106, 22 p.

Droullard, R. F., T. H. Davis, E. E. Smith, and R. F. Holub, 1984
Radiation Hazard Test Facilities at the Denver Research Center:
U. S. Bur. Mines Inf. Circ. 8965, 22 p.
The Bureau of Mines has developed test facilities for use in a research program that deals with radiation hazards in mining. This report describes the radon test chamber located at the Denver Research Center and the Twilight experimental mine located near Uravan, CO.

Droullard, R. F., and R. F. Holub, 1977
Continuous Working-Level Measurements Using Alpha or Beta Detectors:
U. S. Bur. Mines Rept. Investigations 8237, 14 p.
The Bureau of Mines has investigated techniques of using gross alpha or beta detectors to continuously measure working levels. Both methods measure radioactive particulates collected on a filter paper using a constant airflow. Inherent-error studies indicate a value of about +/- 3 percent for the gross alpha method and about +/- 8 percent for the beta method in typical mine atmospheres. However, the beta method avoids problems associated with alpha detectors and is therefore more useful. Applications of these continuous working-level detectors include work area monitoring of exposure levels in underground openings, such as mines and caves, and calibrating personal dosimeters exposed over extended time intervals.

Droullard, R. F., and R. F. Holub, 1985
Continuous Radiation Working-Level Detectors:
U. S. Bur. Mines Inf. Circ. 9029, 20 p.

The Bureau of Mines has used gross alpha and gross beta detectors to continuously measure radiation working levels for a number of years. During this time, improvements have been made in the design and performance of continuous working-level (CWL) detectors. This report discusses the improved designs and some of the operating principles and applications of CWL detectors in the measurement of radon daughter products in mines and dwellings.

Edwards, John C., and Robert C. Bates, 1980
Theoretical evaluation of radon emanation under a variety of conditions:
Health Physics, 39: 263-274

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Control of radiation hazards in underground uranium mines, in Gomez, Manuel, ed., Radiation Hazards in Mining: Control, Measurement, and Medical Aspects, International Conference, Golden, Colo., October 4-9, 1981:
Golden, CO, Colorado School of Mines, Chap. 69, p. 441-446

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Polymeric sealants may provide effective barriers to radon gas in uranium mines:
Engineering Mining Jour., 176(9): 116-118

Franklin, John C., and Randall F. Marquardt, 1976
Continuous radon gas survey of the Twilight Mine:
U. S. Bur. Mines, Metal-Nonmetal Health and Safety/Health Program, Tech. Prog. Rept. 93, 16 p.

Franklin, John C., Thomas O. Meyer, and Robert C. Bates, 1977
Barriers for Radon in Uranium Mines:
U. S. Bur. Mines Rept. Inv. 8259, 24 p.
Water-based epoxy sealants were examined during a 2-year period to determine their effectiveness as barriers to radon release in uranium mines. Radon emanation rates from uranium ore samples were monitored for extended periods in the laboratory before and after sealant application. Reduction of radon flux due to the coating of laboratory samples was approximately 80 percent. Test chambers in a dormant uranium mine were monitored to determine both short and long-term barrier effectiveness. These field studies of the sealants indicated radon flux reductions exceeding 50 percent relatively soon after application and nearly 75 percent about 1 year later. An unexpected complication to early monitoring in the form of a large radon emanation increase, believed due to added moisture, is discussed.

Franklin, J. C., T. O. Meyer, R. W. McKibbin, and J. C. Kerkering, 1976
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Mining Engineering, 30(6): 647-649

Franklin, J. C., C. S. Musulin, and R. C. Bates, 1980
Monitoring and control of radon hazards, in International Mine Ventilation Congress, 2d, Reno, Nev.:
Proceedings, p. 405-411

Franklin, John C., Lee T. Nazum, and Adare L. Hill, 1975
Polymeric Materials for Sealing Radon Gas Into the Walls of Uranium Mines:
U. S. Bur. Mines Rept. Investigations 8036, 26 p.
The Bureau of Mines conducted extensive laboratory and limited field tests to determine whether a polymeric material could effectively reduce the emanation rate of radon gas from uranium ore. In the laboratory 46 different single-coat materials and 14 two-coat applications were tested. The laboratory tests showed that up to 100 percent of the radon gas could be sealed into the rock. Materials tested in the laboratory were polyesters, furan resins, epoxies, latices, and totally inorganic coatings. From the laboratory work six different materials were selected for field testing. The first test was single-coat materials in five static chambers; the second test used two-coat applications in an open chamber. Both tests were conducted in the Dakota mine at Grants, N. M. During the second test, the emanation rate of radon was reduced up to 62 percent.

Franklin, J. C., R. J. Zawadski, T. O. Meyer, and A. L. Hill, 1976
Data-Acquisition System for Radon Monitoring:
U. S. Bur. Mines Rept. Investigations 8100, 19 p.
A data-acquisition system was designed by the Bureau of Mines to monitor five detectors with radon continuously flowing through each. These detectors could be monitored up to 12 times an hour, but were only monitored according to a preset time, thus allowing radon to be monitored continuously in a uranium mine. The counter can be set to monitor each detector for any period of time up to 16.5 minutes. This allows very low concentrations to be monitored longer to reduce statistical error. There would be no upper limit in radon concentration that could be monitored, but there would be a lower limit of 50 pCi/L. Each detector was calibrated in the laboratory by the Lucas flask method. Multiple samples were taken at two different concentrations, and the correction factors for each detector was determined by a least squares fit of the data. To verify the calibrations, a series of measurements at several concentrations (300 pCi/L) with the two-filter method was within 3 percent; thus, the total error would be this difference plus the two-filter error. At high concentrations the coefficient of variation ranged between 2.1 and 9.8 percent for the five different detector units.

Holub, R. F., 1984
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Radiation Protection Dosimetry, 7(1-4): 155-158
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Holub, R. F., and P. J. Dallimore, 1981
Factors affecting radon transport and the concentration of radon in mines, in Gomez, Manuel, ed., Radiation Hazards in Mining: Control, Measurement, and Medical Aspects, International Conference, Golden, Colo., October 4-9, 1981:
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"...The laboratory experiments performed involved measurements of diffusion and emanation coefficients, porosity and permeability of representative rock samples. Significant differences have been found when comparing

the results of the laboratory permeability determinations to those of the mine determinations. Considerations of underlying principles, however, suggest that the diffusion and emanation coefficients are the same in laboratory and mine. It was also found that moisture content plays a dominant role in radon transport through rock...."

Holub, R. F., and R. F. Droullard, 1978
Radon Daughter Mixture Distributions in Uranium Mine Atmospheres:
U. S. Bur. Mines Rept. Investigations 8316, 20 p.
The Bureau of Mines has made a study of the magnitude of the variations of radon daughter mixtures, with the objective of determining whether these variations reflect the existing physical conditions in uranium mine atmospheres or if they are merely random or systematic errors. To accomplish this, many data have been plotted using a triangular graphing technique which shows that plateout affects Po-218 more than Pb-214 or Bi-214, and that it is impossible to find simple correlations between working level ratios, radon daughter mixtures, and age.

Holub, R. F., R. F. Droullard, T. B. Borak, W. C. Inkret, J. G. Morse, and J. F. Baxter, 1985
Radon-222 and Rn-222 progeny concentrations measured in an energy-efficient house equipped with a heat exchanger:
Health Physics, 49(2): 267-277

McVey, James R., John C. Franklin, and David M. Shaw, 1977
Portable instrument measures four ventilation parameters:
Mining Congress Jour., 63(4): 49-52
A four-parameter measurement system for accurate determination of relative humidity, temperature, mine pressure and ventilation velocity has been developed for use in the radon control research of the U. S. Bureau of Mines. The new unit is housed in a 17-by 20- by 8-in. suitcase weighing less than 15 pounds.

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Golden, CO, Colorado School of Mines, Chap. 118, p. 790-793

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Falling barometer nullifies rock sealant effectiveness:
Mining Engineering, 29(6): 38-39

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